VALIDATION OF BUILDING SIMULATION PROGRAMS

Final project report

Coordinating organizations

Tata Energy Research Institute (India)
&
University of Siegen (Germany)

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❶ Introduction

Building designers have traditionally employed a wide range of methods to ensure that the performance characteristics of a building would confirm to building energy standards and would be acceptable by its occupants. Typically, simple (and sometimes not so simple) calculations and rules of thumb are applied throughout the design process to minimize (or maximize) heat losses, maximize the utilization of solar energy, prevent inefficient plant operation, ensure high comfort satisfaction, control problematic air movement and so on. In recent years, researchers have stressed the futility of attempting to optimize, in such a piecemeal manner, a system which is inherently dynamic, non-linear and highly systemic.

In an attempt to address this complexity, and provide effective design decision support, the subject of building simulation has received growing attention in recent years. A simulation model will usually attempt to represent the spatial and temporal aspects of a building and its environmental control system in an exacting manner, although some processes may be simplified because of state-of-art limitations or they are unnecessary in terms of application scope of the model. Many contemporary building energy models are hybrid in the sense that the simulation techniques are mixed with decoupled, often simplified algorithms.

The emergence of simulation as a tool for assessing building performance by those outside the academic research community has been given a boost by the increasing power and lowering prices of PCs and workstations. The use of building simulation programs is becoming a standard technique for performing energy analysis of commercial buildings. However, a program to be useful and acceptable, it must first be demonstrated that it provides permissible accuracy if it is to form the basis of design selections and retrofit strategies.

Many simulation programs have been checked over the years, to some extent, and it is not uncommon for the developers to claim that the programs have been validated by them. The quoted validation studies often include one or two experimental studies or comparisons with other so called reference programs. However, a thermal model's accuracy can only be determined if enough validation studies are carried out to evaluate comparisons between predictions and measurements over a wide range of applications.

Based on these ideas, a research project was conceived as a collaboration activity by the

Tata Energy Research Institute (TERI) and the University of Siegen, to gain hand-on experiences on the selected commercial building simulation programs and to compare the results of building simulations with measurements. The computer programs used for the project work were SOMBRERO for the calculation of shading on building exteriors, and SUNCODE and TRNSYS for the thermal analysis of buildings.

Three buildings (one Indian and two German) have been analyzed using these programs which are described in the next chapter, under this project funded by the International Office of DLR, Germany. The three buildings and their characteristics are described in the 3rd chapter, while the results of simulation are discussed in chapter 4. A comparison of the results of the simulations with measurements and its discussion have been presented in chapter 5. The last chapter contains the conclusions from all the assignments completed and reported in the previous chapters.

In addition to the main work, two additional academic exercises, namely the effect of building form on the shading of building exteriors, and a comparison of various radiation processors built into the program TRNSYS have been discussed in the appendices.

❷ The simulation programs

2.1 TRNSYS

TRNSYS is a transient system simulation program with a modular structure. This modular nature of the program provides tremendous flexibility to the user, and facilitates the addition to the program of mathematical models not included in the standard TRNSYS library. The program is well suited for detailed analysis of systems whose behaviour is dependent on the passage of time.

A system is defined to be a set of components, interconnected in such a manner as to accomplish a specified task. For example, a solar water heating system may consist of a solar collector, an energy storage tank, an auxiliary energy heater, a pump and several temperature sensing controllers. Because the system consists of components, it is possible to simulate the performance of the system by collectively simulating the performance of the interconnected components. Hence the modular simulation technique greately reduces the complexity of system simulation because it essentially reduces a large problem into a number of smaller problems, each of which can be more easily solved independently. In addition, many components are common to different systems and, provided that the performance of these components is described in a general form, they can be used in many different systems with little or no modification.

Included with the TRNSYS program are seven utility programs which are briefly described below[1].

1. DEBUG - a stand-alone utility used to test user written component routines for results and/or errors, plus all required support files.
2. PREP - a transfer function generator for wall/roof/partition for use with the single zone model of a building.
3. BID - the building input description program.
4. PREBID - a menu driven pre-processor to BID containing libraries of wall and layer types along with utilities to completely describe a multi-zone building.
5. PRESIM - a graphical pre-processor to TRNSYS where the user connects pictures of thermal energy components together to completely describe the system. PRESIM generates an input file which is read by TRNSYS to run the simulation.

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[1] TRNSYS - Reference Manual. Solar Energy Laboratory, University of Wisconsin-Madison, Madison, WI 53076 USA.

6. TRNSED- a professional front-end for TRNSYS which allows many of the TRNSYS details to be hidden from the user, displaying only that information which is of importance to the user.
7. TRNSHELL - a menu driven environment program housing the editing and plotting functions, context-intensive help, compiling and linking options, the TRNSYS program and all other utility programs.

2.2 SOMBRERO

SOMBRERO is a PC program for calculating the hourly Geometric Shading Coefficients[2] (GSF) and the view factors for an arbitrarily oriented surface surrounded by shading elements. These elements can be part of the surface itself like overhangs, sidewalls etc, or external obstacles like neighbouring houses or trees. A maximum of 300 polygons each with up to 12 points can be handled by the program[3].

The program includes a user-friendly interface and runs on standard DOS with a VGA graphic card. The program contains a simple generator to describe the frequently occuring external obstacles (a house or a tree). A house is described by its height, length and the height and orientation of the roof. Shadows of trees are treated separately because of the variable amount of leaves and the user may define a monthly schedule for the opaqueness of the tree crown.

The user describes the receiver (target) area by defining its azimuth, elevation and its vertex point in a 2- dimensional (u-, v-) reference system called the body system shown in Figure 1. The overhangs and sidewalls, for example, can then easily be created for a target area by declaring their relative elevation or azimuth in the Body system. The origin of the Body system is defined in another 3-dimensional SOE (Surface-of-Earth) reference system fixed to earth. This facilitates the description of various target planes and the obstacles in front of them.

These two coordinate systems are explained in Figure 2 where a facade is shown with two windows. In order to consider the windows as receiver areas for a thermal zone in a building, their positions and dimensions need to be described. The chosen targets being rectangles, these can be defined by a length Δu and a height Δv with respect to the origin u_0, v_0. The elevation and the azimuth of the facade (containing the windows) are then

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[2] The geometric shading coefficient (GSC) is defined as the ratio of the shaded area of the wall at a given hour to its total area.

[3] SOMBRERO v1.0 - Users' Manual. Softwarelabor für Niedrigenergie- und Solararchitektur, FG Bauphysik & Solarenergie, Universität-GH-Siegen, 57068 Siegen, Germany.

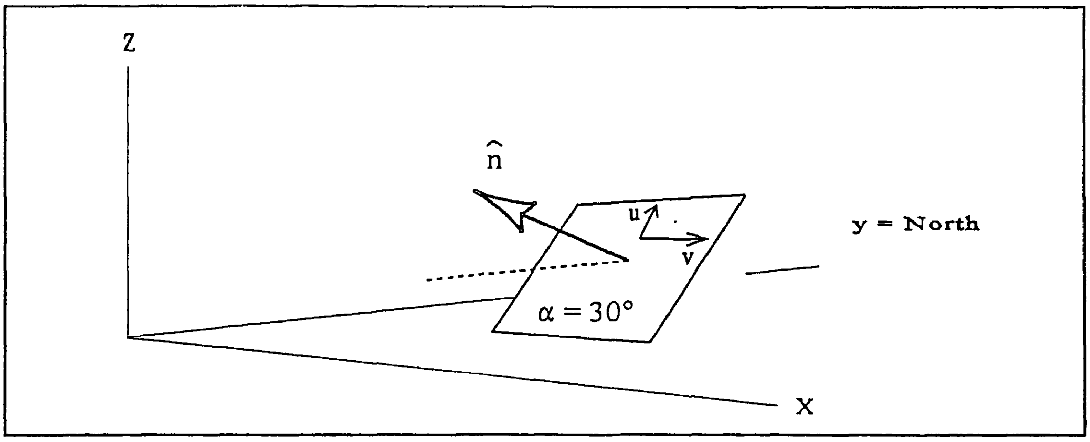

Figure 1: Surface-of-earth-system (SOE-system) with an area oriented to the south. The azimuth α is counted clockwise from the north, i.e. a south-oriented area has an azimuth of 180 °. The elevation angle of the example area is 30 °. The front-side is facing the sky, which is indicated by the normal vector n̂ The u-v-axes indicate the body-system (u-v-system).

defined in SOE- system. The shown facade, for instance, shall have an elevation of 0° and an azimuth of 135°, which is a vertical wall oriented to the south-east. The last step is to tell the module where the origin of the body system would lie in the SOE- system. Hence a site can be defined in its natural coordinates.

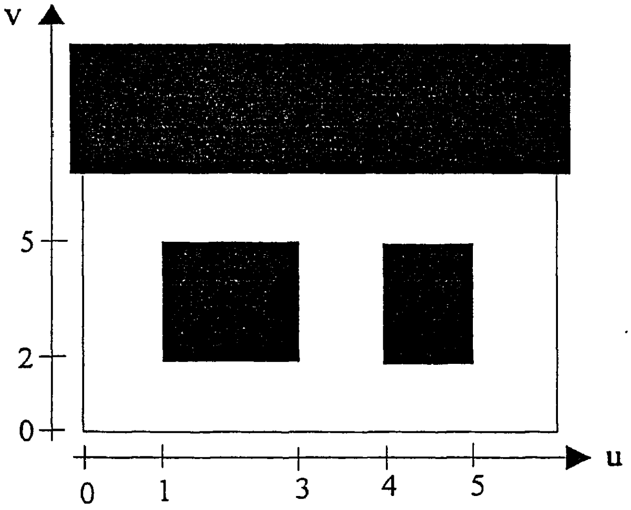

Figure 2: View of a facade with two windows. They are described by their length, height and origin within the u-v-system. The u-v-system is regarded as the body-system of the facade. Units are in meters.

2.3 TRNSYS and SOMBRERO coupling

The shading of the glazed areas from direct solar radiation, and the shading of exterior surfaces by neighbouring buildings, trees etc play an important role in improving the thermal performance of buildings in hot climates/seasons. Since TRNSYS does not have a provision for modeling all the shading devices conveniently, it was imperative to couple it with SOMBRERO to accurately incorporate the influence of the shadings on the buildings under consideration.

SOMBRERO was used to calculate the GSC^s and the view factore (sky and ground) for all the windows and for the external surfaces facing south, west and east directions. The data files containing the hourly values of GSC^s produced by SOMBRERO for each window and external surface were read directly by the corresponding TRNSYS decks[4] during the simulation of the guest house.

The importance of shading on thermal performance of buildings led to a separate academic exercise of studying the effects of shading on various building forms. This exercise and its results are discussed in Appendix A.

2.4 SUNCODE

SUNCODE-PC is a general purpose thermal analysis program for residential and small commercial buildings[5]. It is a PC version of SERI/RES - a mainframe program written for the Solar Energy Research Institute by Larry Palmiter ans Terry Wheeling of Ecotope Inc., Seattle, USA. The program has been extensively tested by the SERI staff and other users using the measured building data over the last decade, and compared with other programs for its accuracy. It is particularly suitable for the analysis of various types of passive solar buildings because special provisions are made for simulating attached sunspaces, thermostatically controlled fans, rockbin thermal storage, and vented Trombe wall. The program allows the user a flexibility in choosing the level of detail to be used in modeling a building.

The method of analysis used in the program is simulation. A thermal model of the building is created by the user. It is then translated into mathematical form by the program. The mathematical equations are solved repeatedly at time intervals of one hour or less for the period of simulation. The mathematical representation of the building is a thermal network with non-linear, temperature dependent controls. The mathematical solution technique uses a combination of forward finite difference, Jacobian iteration, and constrained optimization.

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[4] A deck is the input file prepared by a user for TRNSYS simulation.

[5] SUNCODE v5.5 - Users' Manual. Ecotope Inc., Seattle, USA.

The program has an interactive editor for creating building descriptions, where the user is continuously prompted with headers that provide the names and units for each data entry. This allows for rapid and error free input. The editor also checks the validity of the inputs and reports errors during compilation of the intermediate input file. It also provides facilities for storing and referencing several types of building description files.

❸ The buildings

3.1 SEC guest house in Gurgaon

The guest house situated in the campus of the Solar Energy Centre (SEC) of the Ministry of Non-conventional Energy Sources (MNES), Government of India, has been designed on the principles of passive solar architecture. The SEC campus is located in Gurgaon (Haryana) at a distance of about 40 km from New Delhi. The composite climate of the site is characterized by hot summers (April - June), cold winters (November - February) and three months of high humidity during monsoon (July - September). In order to give an idea of the climate, the monthly averages of the important weather parameters are given in the following table.

PARAMETER	MONTH											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Temperature (°C)												
Maximum	21.3	23.6	30.2	36.2	40.5	39.9	35.3	33.7	34.1	33.1	28.7	23.4
Average	14.3	16.8	22.6	28.6	33.5	34.3	31.2	29.9	29.3	25.9	20.2	15.7
Minimum	7.3	10.1	15.1	21.0	26.6	28.7	27.2	26.1	24.6	18.7	11.8	8.0
Rel. Humidity (%)												
Morning	72	59	47	32	31	48	73	77	70	54	48	63
Evening	41	28	21	16	18	32	60	65	54	35	31	38
Rainfall (mm)	24.9	21.8	16.5	6.8	7.9	65.0	211.1	172.9	149.7	31.2	1.2	5.2
Wind Speed (m/s)	2.3	2.8	3.0	3.0	3.6	4.1	2.9	4.5	2.7	1.8	1.9	2.1
Wind Direction												
Morning	W	W	W	W	W	W	E	W	W	W	W	W
Evening	NE	NE	NE	NW	NW	NW	SE	SE	N	N	N	N
No. of clear days												
Morning	17	17	20	23	25	17	7	6	16	27	27	22
Evening	17	17	18	19	21	16	5	4	16	27	26	20
Radiation (kWh/m^2)												
Global	149	164	216	237	266	265	266	245	209	180	144	131
Diffuse	49	48	55	61	65	63	65	63	53	52	48	46

The main features of the guest house are as follows:

1. The guest house has been built on a south slope of an undulating site, and is partially earth bermed from three sides (Figure 3). The cascaded floors along the slope provide further contact of the building with the ground which is a desirable passive feature in buildings in hot climates. The ground temperature, at a certain depth below earth's surface, is always equal to the annual ambient air temperature. When this temperature lies inside the range of thermal comfort, the ground coupling can be an effective means of improving the indoor thermal comfort, thereby reducing the cooling and heating energy consumption.

2. The roof has a terrace garden which is watered during the summer months. The evaporation of water from the terrace garden not only modifyes the micro-climate at the site but also absorbs a major part of the cooling load in summer. The terrace garden is the second major feature for cooling this building in summer.

   A special section of the roof contains manually operated ventilators to facilitate cross-ventilation of each guest suite if desired by the guest.

   The flower beds directly below and above the windows with regular spraying of water in them, add to the effect of the terrace garden. The air cooled by the evaporation of water can infiltrate directly into the guest suites and produce a cooling effect.

3. The corrugated external surfaces of the building have been finished with white reflective paint to reduce the absorption of the incident solar radiations on the exposed portions of the vertical walls.

4. The windows are protected by arched sunshades (overhangs and sidewalls) of predetermined dimensions to avoid the entry of the direct sun into the building during summer, but to allow it during the winters. The windows have been designed to eliminate air gaps in their construction in order to reduce the unwanted infiltration of the outside air.

5. Solar water heaters integrated with the architectural design have been provided for each bathroom. These collectors have been deliberately placed at a high and visible location so that their state of disrepair (dust accumulation, leaks, breakages etc) can be monitored easily.

6. A sunny terrace has been provided near the kitchen to facilitate solar cooking.

3.1.1 Inputs for the simulation of guest house

The relevent input data used in simulation of the guest house are as follows:

Site	Latitude	28° 35' N
	Longitude	77° 12' E
	Altitude	216 m above mean sea level

For the purpose of simulation, the guest house has been divided into three zones. These zones which can be seen on the building plan of Figure 4, are called:

1. East Zone (suites 1, 2 and 3)
2. West Zone (suites 4, 5, 6 and the office)
3. Lobby (includes the entrance lobby, corridor, dinning hall, kitchen and the lounge)

Floor areas and zone volumes

Zone Name	**Floor Area (m^2)**	**Zone Volume (m^3)** (floor height = 2.9 m)
East Zone	78 9	229
West Zone	91.4	265
Lobby	125.8	365
Total	296.1	859

Wall and window areas (m^2)

Zone Name	**Wall Areas**						**Window Areas**	
	North	East	West	South	Bermed	Ambient#	North	South
East Zone	9 27	29.63	45.88	22.41	49.33	10.32	2.40	11.76
West Zone	9.27	46.90	29.63	22.41	49.51	16.68	2.40	11.76
Lobby	87.07	--	7.89	14.18	20.48	51.93	16.28	17.60

# These areas are exposed to ambient air but not to direct sun

Construction details

Outer Wall	Plaster	0.015m	Internal Wall	Plaster	0.015m
	Brick	0.300m		Brick	0.200m
	Plaster	0.015m		Plaster	0.015m

Floor	Plaster	0.015m	Roof	Plaster	0.015m
	Concrete	0.150m		Concrete	0.150m
				Plaster	0.015m
				Mud	0.250m

Properties of building materials

Material	Density kg/m^3	Conductivity W/m.K	Sp. Heat J/kg.K
Plaster	2000	1.40	837.0
Brick	1200	0.50	837.0
Concrete	2400	2.10	897.0
Mud	1400	0.77	879.0

Monthly ground temperature schedule

(Temperatures in °C at a depth of 1.0 m below earth surface)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
27.6	25.9	20.2	15.7	14.3	16.8	22.6	28.6	33.5	34.3	31.2	29.9

Heat transfer coefficients & other parameters

$H_{outside}$ (wall)	25.0 W/m^2.K	absorptivity$_{outside\text{-}surface}$	0.70
H_{inside} (wall)	08.0 W/m^2.K	absorptivity$_{glass}$	0.09
$H_{outside}$ (window)	25.0 W/m^2.K	U-value$_{glass}$	5.20 W/m^2.K
H_{inside} (window)	05.0 W/m^2.K		

Heating set-point temperature = 18 °C

Cooling set-point temperature = 27 °C

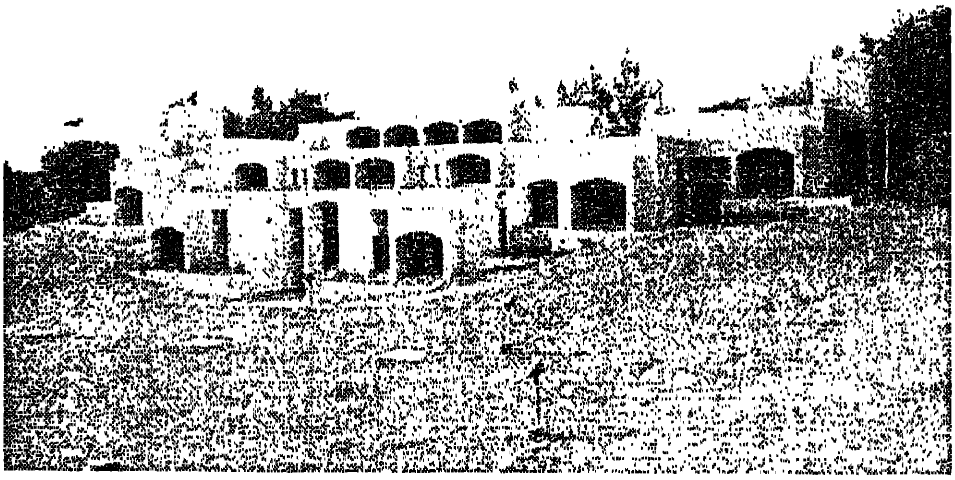

Figure 3: South view of the SEC guest house.

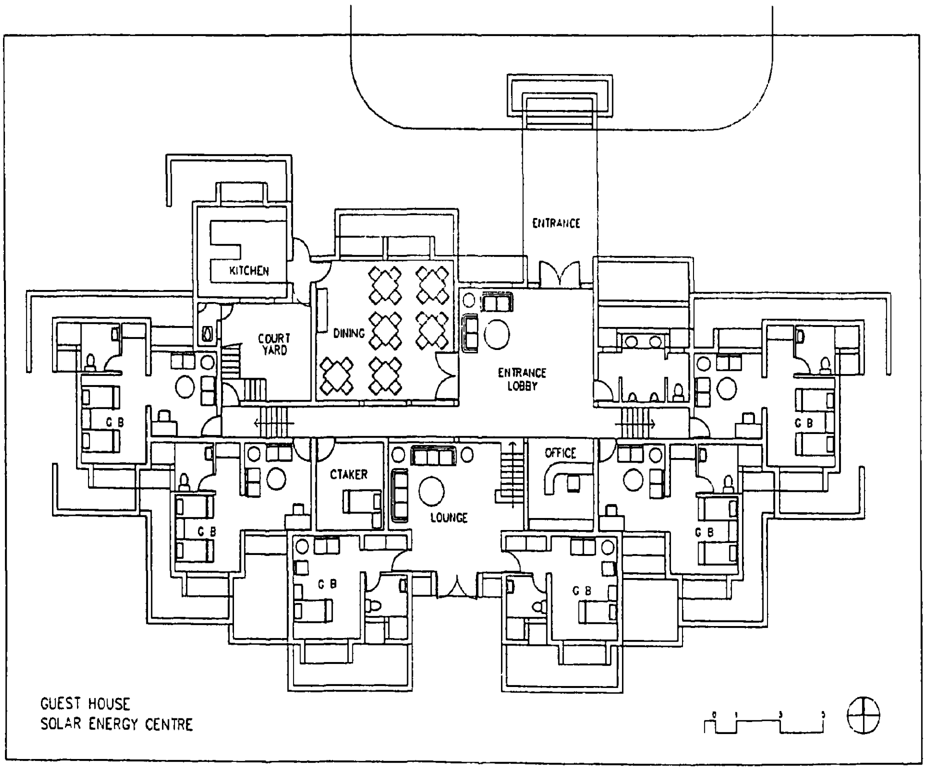

Figure 4: Floor plan of the guest house (scale in meters).

3.2 Office building in Issum

The office building under investigation has been constructed without a basement and with a slightly inclined green roof. The heated floor area is 96.5 m², and the net heated volume is 241.25 m³. The building layout and heating and ventilation systems have been carefully designed to achieve maximum benefit from solar energy. The floor plan of the building is presented in Figure 5.

A large fraction of the south facade of the building is covered by windows. Heat losses through the glass are limited to a minimum by the use of double glazed windows with an average U-value of less than 1.0 W/(m²K). Protection from direct sun in summer is accomplished by an extension of the roof which acts as an overhang on top of the windows. The walls in the north and west are covered by a shelter of earth. By virtue of the open internal design, almost the whole building benefits directly from solar radiation. The floor and all the walls have high thermal capacity in order to achieve a high solar-load-ratio for the passive solar gains.

The fresh air for the ventilation is preheated with a heat recovery system if the floor heating system does not meet the actual heat demand of the building. The heat for both the floor heating system and the preheating of the fresh air is supplied by a hot-water reservoir which is operated by a ground-water heat pump. The low temperature level of the reservoir (below 35°C) yields a good efficiency of the heat pump. The floor heating system operates at a temperature of about 25°C without causing overheating of the indoor air.

3.2.1 Inputs for the simulation of Issum office building

Site

Latitude	: 51.3° N
Longitude	: 06.3° E
Altitude	: 100.0 m above mean sea level

Zone height:

Lobby	2.3 m
Office	2.5 m
Store	2.4 m

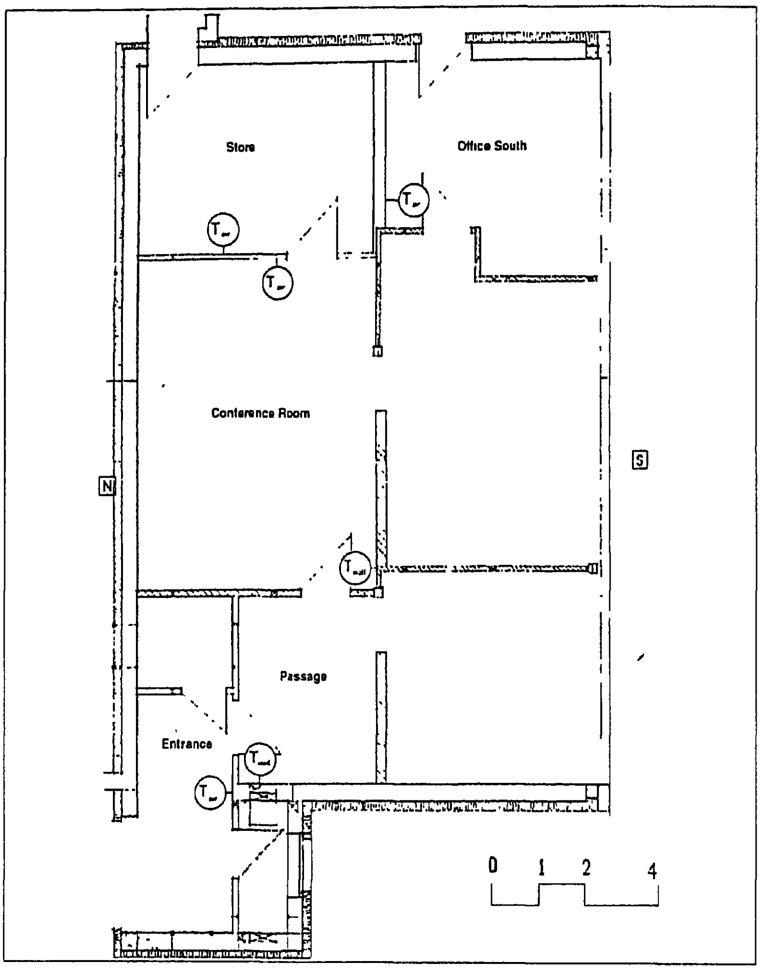

Figure 5: Floor plan of Issum office (scale in meters)

Construction details:

Outer wall	Plaster	0.015 m	Inner walls	Plaster	0.015 m
	Brickwork	0.300 m		Hollow Block	0.115/0.24m
	Insulation	0.180 m		Plaster	0.015 m
	Plaster	0.025 m			
Floor	Laminate	0.001 m	Ceiling	Wood	0.044 m
	Flooring	0.100 m		Insulation	0.120 m
	Insulation	0.060 m		Earth	0.200 m
	Concrete	0.200 m			
	Insulation	0.060 m			

Properties of building materials:

Material	Conductivity W/(m.K)	Density kg/m³	Sp.Heat kJ/(kg.K)
Plaster	0.700	1400.0	0.960
Brickwork	0.700	1400.0	1.000
Insulation (Walls/Floor)	0.040	0030.0	1.500
Insulation (Ceiling)	0.035	0043.0	1.500
Flooring	1.400	2000.0	0.920
Concrete	2.100	2400.0	1.000
Wood	0.130	0600.0	1.700
Laminate	0.130	0600.0	0.960
Earth	1.200	1400.0	2.235

Floor/Roof areas (m^2):

Lobby	14.6/ 20.7
Office	96.5/ 111.0
Store	16.3/ 21.3

Wall and Window Areas (m^2)

Orientation	Lobby		Office		Store	
	Wall[#]	Window	Wall	Window	Wall	Window
North	15.1	-	32.6	-	8.8	-
East	8.7	-	25.2	-	12.8	-
West	9.3	-	25.2	-	12.8	-
South	14.8	0.75	2.7	37.6	10.0	-
Total Area	47.9	0.75	85.7	37.6	44.4	-

[#] The wall area does not include the window area.

Seasons

Summer : Jun 1 - Aug 31
Autumn : Sep 1 - Oct 31
Winter : Nov 1 - Mar 31
Spring : Apr 1 - May 31

edules:

Parameter	Season	Hour	Value	Hour	Value
ltration r changes per ır)	OFFICE				
	Summer	08	0.2	19	0.4
	Winter	10	0.4	17	0.3
	Autumn	08	0.2	19	0.4
	Spring	06	0.4	18	0.2
	STORE				
	Summer	08	0.05	19	0.2
	Winter	08	0.1	19	0.1
	Autumn	08	0.05	19	0.2
:rnal gain N)	OFFICE				
	Year (weekdays)	08	0.2	18	0.02
	STORE				
	Summer	08	0.0	18	0.0
	Winter	08	0.15	18	0 1
vable Insulation /m^2.K)	Year	08	0 92	20	0.50

ıthly ground temperatures

peratures in °C at the depth of 1.0 m below earth surface)

N	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3	07.3	09 8	12.3	14.0	14.5	13.6	11.7	09.1	06.6	04.9	04.4

Ground reflection coeff. : 0.20

Wall absorptivity (exterior) : 0.70

Heat transfer coefficients (W/m^2.K)

- Wall (outside) : 25.0
- Wall (inside) : 08.0
- Ceiling : 08.0
- Roof : 25.0
- Floor (inside) : 08.0

} Multi-family house in Witten

multi-family house in Witten, Germany selected for study is a residence for three lies living at different floors in it. The site is characterized by 3740 heating degree-days, age medium wind speeds and an annual average ambient air temperature of 7.2 °C.

The house has lightweight construction, with large windows on the south facade to benefit largely from solar energy. The windows are made of special heat protecting (high thermal resistance) glass to conserve the heat inside the building. Adequate amount of insulation has been used inside walls and roof. The plans of the cellar and ground floors are shown in Figures 6 (a,b).

3.3.1 Inputs for the simulation of the multi-family house in Witten

Site		
	Latitude	: 51.3° N
	Longitude	: 07.2° E
	Altitude	: 100.0 m above mean sea level

Zone height:		
	Cellar	2.5 m
	Ground floor	2.6 m
	First floor	2.2 m

Construction details:

Outer Wall (1)	Plaster (Gipsum)	0.029 m
	Hollow Block (Poroton)	0.36/ 0.24/ 0.175 m
	Insulation (Tektolan)	0.06 m
	Plaster	0.029 m
Outer Wall (2)	Plaster (Gipsum)	0.029 m
	High quality wood	0. 012 m
	Insulation (Isofloc)	0.20/ 0.24 m
	Insulation (Heraklith)	0.035 m
	Plaster	0.029 m
Roof	Plaster (Gipsum)	0.029 m
	Wood	0.20 m
	Insulation (Isofloc)	0.20/ 0.24 m
	Insulation (Gutex)	0.02 m
Ceiling	Plaster (Gipsum)	0.029 m
	High quality wood	0. 012 m
	Wood	0.20 m
	Insulation (Heraklith)	0.035 m
	Plaster (Gipsum)	0.029 m
Floor	Floor Board	0.02 m
	Insulation (Tektolan)	0.06 m
	Reinforced Cement Concrete	0.12 m
	Insulation (Glasfoam)	0.08 m

(Note: Isofloc, Heraklith, Gutex and Tektolan are the brand names of these materials)

Properties of building materials

Material	Conductivity W/m²K	Density kg/m³	Sp. Heat kJ/kg.K	Thickness m
Plaster (Gipsum)	0.70	800.0	1.000	0.029
Hollow block	0.33	800.0	1.000	0.36/0.24/0.175
Reinforced Cement Concrete	2.10	2200.0	1.000	0.12
Quality wood	0.14	700.0	2.100	0.012
Wood	0.14	700.0	2 100	0 20
Floor Board	0.14	700.0	2.100	0.02
Insulation (Heraklith)	0.09	400.0	1.000	0.035
Insulation (Tektolan)	0.045	160.0	1 300	0 06
Insulation (Gutex)	0.05	160.0	1.300	0.02
Insulation (Isofloc)	0.045	120.0	1.300	0.20/ 0.24
Glasfoam	0.05	120.0	1.500	0 08

Wall and Window Areas (m²)

Orientation	Cellar		Ground Floor		First Floor	
	Wall #	Window	Wall	Window	Wall	Window
North	34.00	02.44	34.00	06.16	34.00	04.28
East	35.00	01.72	35.00	04.76	35.00	02.79
West	35.00	02.59	35.00	05.79	35.00	04.31
South	34.00	07.04	34.00	06.89	34.00	11.69
South-East	15.20	04.16	15.20	05.53	15.20	02.00
South-West	06.20	02.09	06.20	02.77	--	--
Total Area	159.40	20.04	159.40	31.90	153.20	25.07

wall area includes the corresponding window area.

Floor/Roof areas:

Cellar 1 (heated)	86.0 m^2
Cellar 2 (unheated)	69.4 m^2
Ground Floor	155.4 m^2
First Floor	155.4 m^2
2 x Roof (45°)	2 x 17.5 m^2
2 x Roof (27°)	2 x 60.0 m^2

Seasons:

Summer : Jun 1 - Aug 31
Autumn : Sep 1 - Oct 31
Winter : Nov 1 - Mar 31
Spring : Apr 1 - May 31

Schedules:

Parameter	Season	Hour	Value	Hour	Value
Infiltration (Air changes per hour)	Winter, Spring and Autumn	06	0.4	18	0.2
	Summer	06	0.4	-	-
Movable Insulation (W/m^2.K)	Winter	08	1.3	18	0.5
	Summer	08	1.3	18	1.3

Heat transfer coefficients (W/m^2.K):

Wall (outside) : 23.0
Wall (inside) : 08.0
Ceiling : 08.0
Roof : 23.0
Floor (inside) : 08.0

Ground reflection coeff. : 0.2

Wall absorptivity (exterior) : 0.70

Heating set-point temperature : 19.7°C (in Cellar 1, ground and first floor)

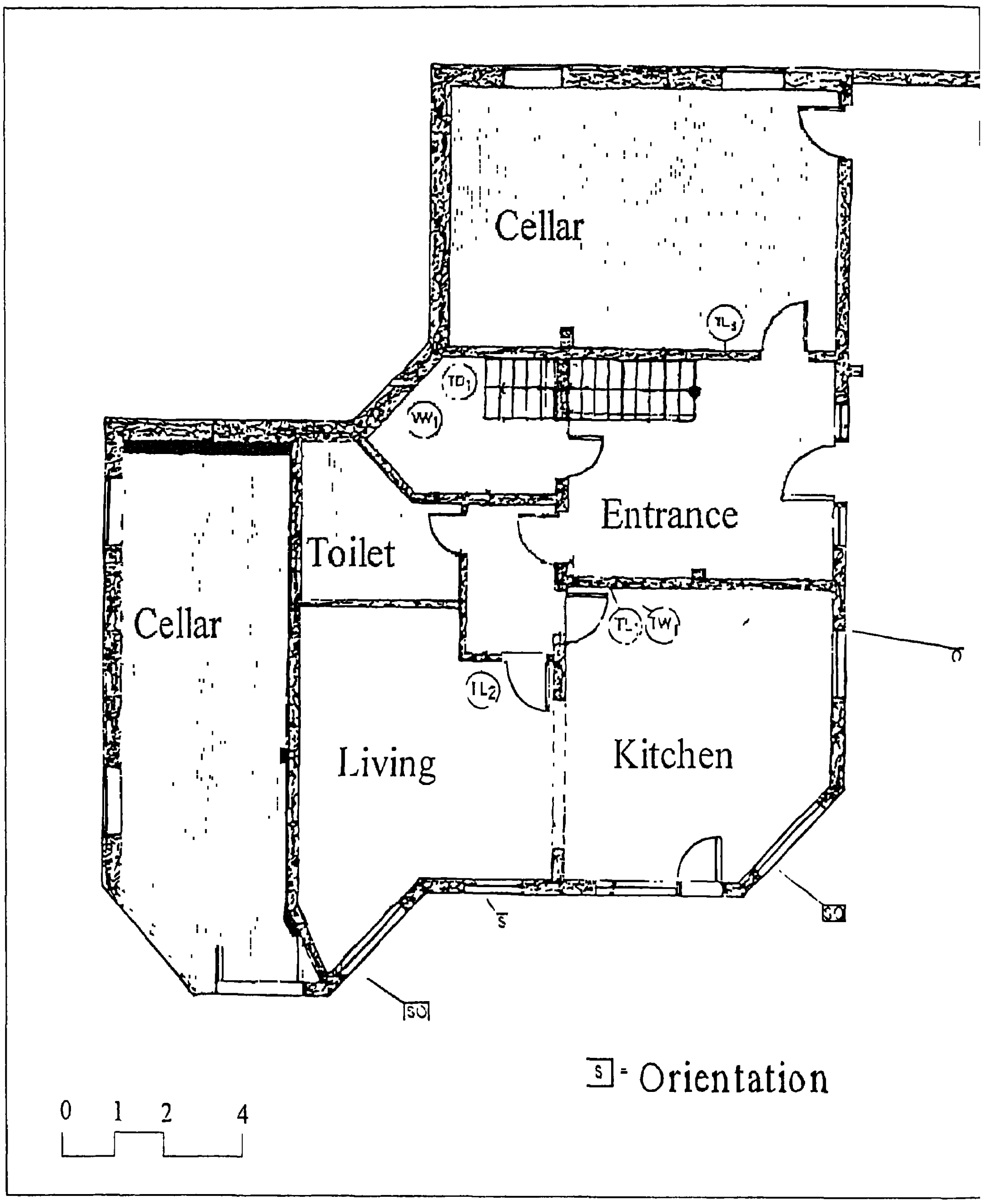

Figure 6 a: *Floor plan of the cellar in the multi-family house. The positions of the sensors are also marked in the diagram (TL_n: air temperature, TW_n: wall temperature). The unheated areas are shaded to distinguish them from the heated portion (scale in meters)*

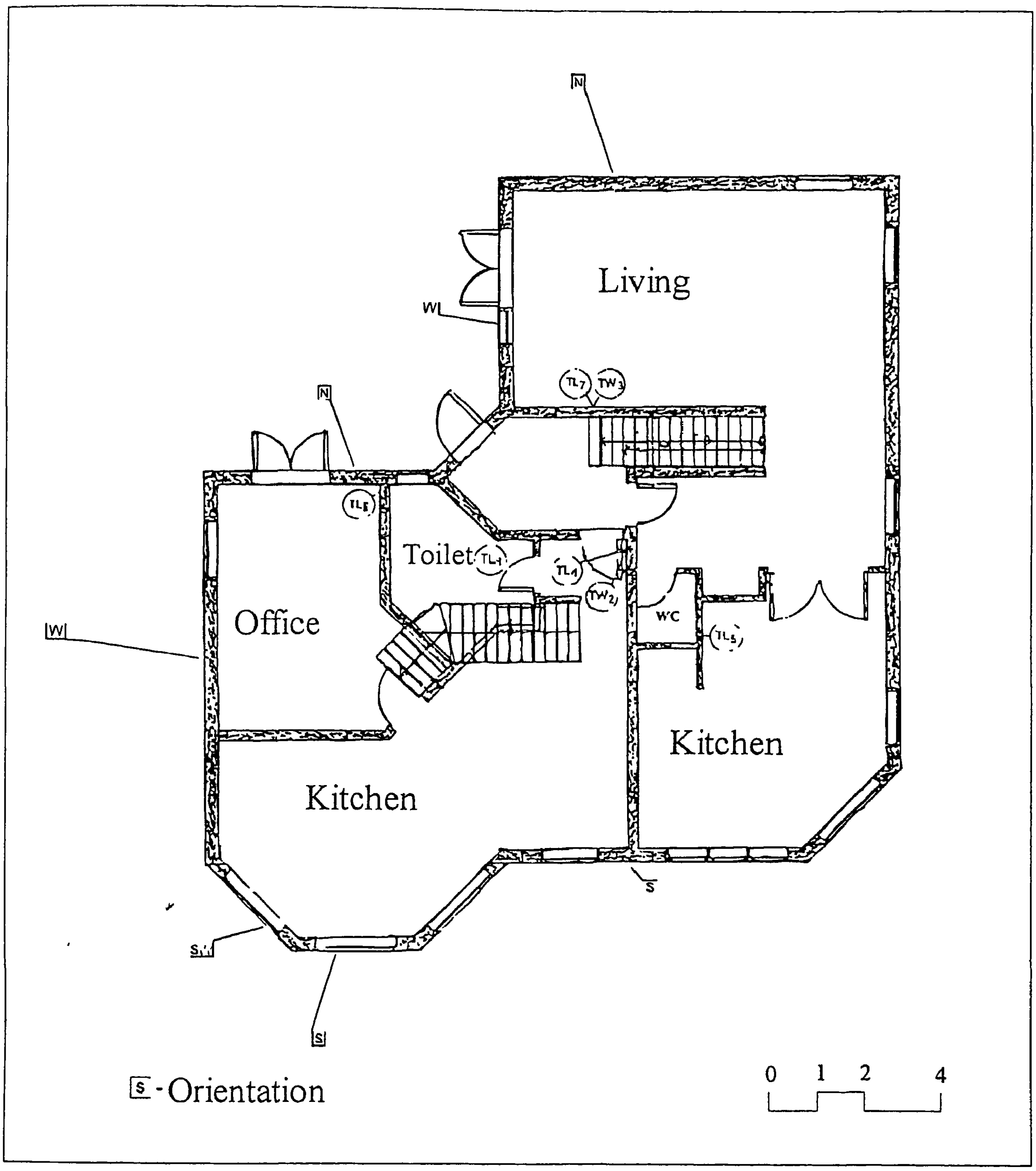

Figure 6 b: Ground floor plan of the multi-family house showing the positions of the sensors (scale in meters).

❹ Results of simulation

4.1 Simulation of SEC guest house

The SEC guest house was simulated for the following five cases using the input data mentioned in section 3.1.1. The basic idea behind these simulations was to find out the quantitative effect of each passive feature of the house on its thermal performance.

Case 1: (EXISTING)	The actually constructed guest house but the solar water heating collectors were not considered because they have been dismantled for a long time from the building.
Case 2: (NO BERM)	The existing guest house simulated without earth berming i.e. the bermed portions of the walls have been exposed to outside, in order to study the effect of berming.
Case 3: (NO SHADE)	The existing guest house considered without the shading of windows by overhangs and sidewalls. This case gives an idea of the effect of shading on thermal performance of the building.
Case 4: (NO GR ROOF)	The existing guest house is simulated without the terrace garden.
Case 5: (ALL)	The cases 2, 3 and 4 have been combined here to theoretically convert the guest house into a non-solar building. This simulation case gives and idea of the efficiency of a solar house as compared to an ordinary non-solar house.

The simulation results of all the above mentioned cases are printed as Figures 7-14, and are explained below:

4.1.1 Zone temperatures

Daily average temperatures in the zones are plotted for a complete year in Figure 7, indicating that the temperatures lie in the comfort range for nearly half the year. The maximum temperature in summer reaches about 35°C in the lobby and 33°C in the guest suites, and sinks to about 15°C in winter for a short period. The average temperature curves for the two zones (east and west zones) almost coincide throughout the year, and are slightly different from that for the lobby.

4.1.2 Cooling and heating loads

Cooling and heating loads for the guest house are calculated for fixed set-point temperatures (the heating starts when the zone temperature sinks below 18°C, and the cooling becomes functional when the zone temperature starts to increase above 27°C). The zone air temperatures would sometimes go beyond this range of defined set-points, therefore the house would require some energy to maintain itself within this range of conditions.

The monthly cooling loads in Figure 8 obviously increase with the removal of each passive feature from the building, and are maximum for the combined case. The cumulative extent of influence of each feature can be seen in the annual cooling load in Figure 10. The results indicate that the passive features reduce the annual cooling load by about 50%, and increase the period of indoor thermal comfort (comparison of daily average temperatures in Figure 11). The results show that the contributions of earth berming, shading devices and the terrace garden to the reduction of cooling load are approximately 9%, 18% and 37% respectively.

The existing guest house has almost no heating energy requirements (Figure 9) in winter. The chosen value of infiltration causes heat losses during the remaining months of year, but interestingly do not account for any heat load during winter. Heating energy is required if the earth shelter or the terrace-garden is removed.

4.1.3 Infiltration

A fixed value of infiltration rate (1.0 air change per hour which is necessary for hygienic considerations) has been used during the simulation in all the cases. The heat losses and gains for each month, resulting from infiltration are plotted in Figure 12. The infiltration causes heat gains during the months of April - August, which account for about 5% of the annual cooling load.

4.1.4 Ventilation

The ventilation taking place in the bulding has been modeled according to the following criterion.

Ventilation is switched on when:	*Zone Temperature > Ambient temperature* *AND* *Zone Temperature > 24°C*
Ventilation rate: *(Air changes per hour)*	*[Zone temp. - Amb. Temp.]/2 or a max. of 5.0*

The major effect of the ventilation has been the night time cooling of the building, specially during the months of March, April and September - November.

As seen in Figure 13, the increase in the heat losses due to ventilation for the cases 2, 3 and 4, is due to the fact that the zone temperature is higher at any given time than in the case 1 of the existing guest house.

4.1.5 Solar gains

The windows in the guest house are protected by overhangs and sidewalls of appropriate dimensions. Hence, the solar gains in summer are lower than those in winter (Figure 14). The solar gains in cases 1, 2 and 4 are the same because of the similar shading patterns. However, the solar gains increase to more than 2 times in case 3 when the shading devices are removed.

A slight difference in solar gains in the cases 3 and 5 is due to slightly different frame areas of the windows used in the two cases. In TRNSYS, the frame area is an hourly variable in order to take the effects of shading by overhangs and sidewalls.

4.2 Modification of the guest house to suite German climate

An academic interest was persued by further simulating the guest house under German weather conditions, for which the representative climate of Würzburg was considered. The change in the thermal behaviour of the building was studied through the following three exercises.

Exercise 1: The existing guest house was simulated using the weather data from Würzburg.

Exercise 2: The construction of the guest house was theoretically modified according to German building standards (WSVO)[6], and simulated again using the weather data from Würzburg. The modifications considered were:

- Addition of insulation on walls, roof and floor,
- Replacement of single glazed windows by double glazed windows,
- Improvement in the air-tightness of the building, and
- Removal of shading devices to increase solar gains through windows.

Exercise 3: The modified guest house was simulated once again as if situated in Gurgaon (with the climate of Delhi), to study the performance of a German standard house in India.

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[6] H. Ehm· Wärmeschutzverordnung 1995: Der Weg zu Niedrigenergiehäusern. Bauverlag GmbH, Wiesbaden, Berlin, 2. Auflag. 1996

4.2.1 Results of modification and their discussion

The results of the above mentioned three simulation exercises are shown in Figures 15 - 17. It may be noted that only heating loads are considered for German weather conditions while cooling loads are calculated for Indian conditions.

Guest house in German climate

The heating loads obtained by simulating the existing and theoretically modified guest houses are plotted in Figure 15 which show that the performance of the existing house in the climate of Würzburg is extremely poor. The annual heating loads for each unit of floor area are calculated as 470 kWh/m^2/year for the existing house which reduce to about 100 kWh/m^2/year after modification.

The basic characteristics of the house calculated according to the European standard (EN 832)[7] in both the cases are tabulated below.

Parameter	**Existing guest house**		**Modified guest house**	
	Quantity kWh/m^2	Percentage of total gain/loss	Quantity kWh/m^2	Percentage of total gain/loss
Heat gains				
-Solar	86.0	14	75.2	35
-Internal	39.4	6	39.4	18
-Heating	506.2	80	101.7	47
Heat losses				
-Roof	162.2	27	29.8	17
-Walls	110.8	18	25.5	14
-Windows	112.7	18	36.9	21
-Floor	166.7	27	24.8	14
-Infil./Ventil.	59.4	10	59.4	34

Modified guest house in Indian conditions

The monthly cooling loads that resulted from the simulation exerecise 3, are compared with the previous results (section 4.1 - Figure 8) in Figure 16. The cooling loads in the modified house are smaller during the months of June - September. Although the annual cooling load hardly changed from 69.1 kWh/m^2/yr to 68.9 kWh/m^2/yr when the modified house as such was simulated in the climate of New Delhi, but a decrease in the cooling load was observed after resuming the cooling of the house by favourable ventilation and the shading of walls and windows. Figure 16 already contains the effects of these two phenomenon which reduce the annual cooling load by 44% in the modified guest house.

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[7] N.N.: Entwurf DIN EN 832 - Wärmetechnisches Verhalten von Gebäuden, Beuth-Verlag GmbH, Berlin 1992

The modifications considered for the guest house to improve its performance in the German climate, would however, need a cost benefit analysis when being suggested for the Indian climate under consideration.

Finally, the monthly solar gains (Figure 17) decrease in the modified house as a result of using double glazed windows in place of the existing single glazed ones (the solar gains of Figure 14 are reproduced here). The annual solar gains are 16.6 MWh/m^2/year and 13.6 MWh/m^2/year respectively for the existing and the modified guest houses.

4.3 Simulation of the Issum office building

Issum office was simulated by SUNCODE and TRNSYS using the input description mentioned in section 3.2.1. The results of simulation by SUNCODE are mentioned here while the similar results of TRNSYS simulation are used for comparison in the next chapter.

The daily average temperatures in the three zones of the building are shown in Figure 18, along with the measured ambient temperature for the entire year. A heating set-point of 17.2°C is clearly seen in the temperature profile for the office zone. The value of the heating set-point which has been chosen after observing the measured temperatures, is confirmed also from the frequency distribution of the measured temperatures[8].

The lobby and the store are not heated but the higher temperatures in store are the result of air exchange between the store and office due to the frequent opening of the door between them. The store forms a part of the passage between the office building and the adjacent residence. The maximum and minimum temperatures obtained in the unheated lobby are 26.5°C and 12.7°C respectively. The figure also indicates that the office does not require heating when the daily average ambient is higher than 10°C.

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[8] A. Schwab and D. Schulze-Kegel 1996. Energetische Diagnose von Gebäuden. Project report, FG Bauphysik und Solarenergie, Universität-GH-Siegen, Germany.

Heating period during a year can be seen in the monthly energy balance plotted as a bar chart (Figure 19). The monthly sums of solar gain, heat exchange through windows and walls (ambient), heat losses to the ground and due to infiltration are plotted as stacked bars where the following observations can be made.

1. The heating season includes the months of January - April, November and December. The maximum heat load occurs during the month of December when a maximum plant capacity of 1.95 kW is required. Annual heating demand is 29.8 kWh/m^2/year.
2. The building looses heat through opaque areas in its exterior (walls and roof) during most part of the year, excluding only the months of July and August when the building gains heat.
3. Solar energy contributes nearly 50% of the total energy requirement for heating.
4. The loss of heat through glazed areas (windows) and through infiltration always exceed the day-time gains. Hence the net balance for any month is the loss of heat.
5. The building, on the monthly average, always looses heat to the ground.

Other characteristics of the house exhibited by the simulation are:

Building heat loss rate to the ambient = 100.8 W/K
= 0.79 W/K/(unit floor area)
Building heat loss rate to the ground = 35.9 W/K
Total building heat capacity = 252.7 MJ/K

Properties of the building construction :

Building Element	Thermal Conductance (W/m^2.K)
Outer wall	0.200
Floor	0.315
Roof	0.285
Internal wall (115)	4.772
Internal wall (24)	2.592
Internal wall (30)	2.121
Internal wall (65)	0.309

4.4 Simulation of the multi-family house in Witten

In a similar manner to that described in the previous section, the multi-family house in Witten was also simulated by SUNCODE and TRNSYS using the input data from the section 3.3.1.

The daily average air temperatures in the four defined zones, namely cellar (unheated), cellar (heated), ground floor and first floor, are plotted in the line chart (Figure 20), while the monthly energy balance is plotted in Figure 21. Once again the set-point temperature (19.7 °C) has been chosen after an inspection of the measured temperatures in order to obtain a good match between the measured and simulated data.

The observations made in these figures are as follows:

1. The maximum and minimum temperatures in the unheated cellar are 26.5°C and 12.7°C respectively.
2. The temperatures in the heated areas lie between the set-point and 28°C (in summer).
3. The heating season extends over nine months for the house, and excludes the months of June - August. However, the monthly energy required for heating the house is smaller than in a conventional house. Annual heating demand is 34.4 kWh/m^2/year (SUNCODE) and 44.9 kWh/m^2/year (TRNSYS).
4. Solar energy contributes up to 40% of the total energy required for heating.
5. The house looses heat throughout the year to the ground and through the windows and walls.

Other properties of the house that resulted from the simulation are:

Building heat loss rate to the ambient = 271.9 W/K
= 0.58 W/K/(unit floor area)
Building heat loss rate to the ground = 40.4 W/K
Total building heat capacity = 236.5 MJ/K

Properties of the building construction :

Building Element	Thermal Conductance ($W/m^2 K$)
Outer wall (1)[#]	0.878
Outer wall (2)[#]	0.474
Outer wall (3)[#]	0.523
Outer wall	0.201
Floor	0.319
Ceiling	0.512
Roof (27°)	0.171
Roof (45°)	0.202

[#] The outer walls of the cellar

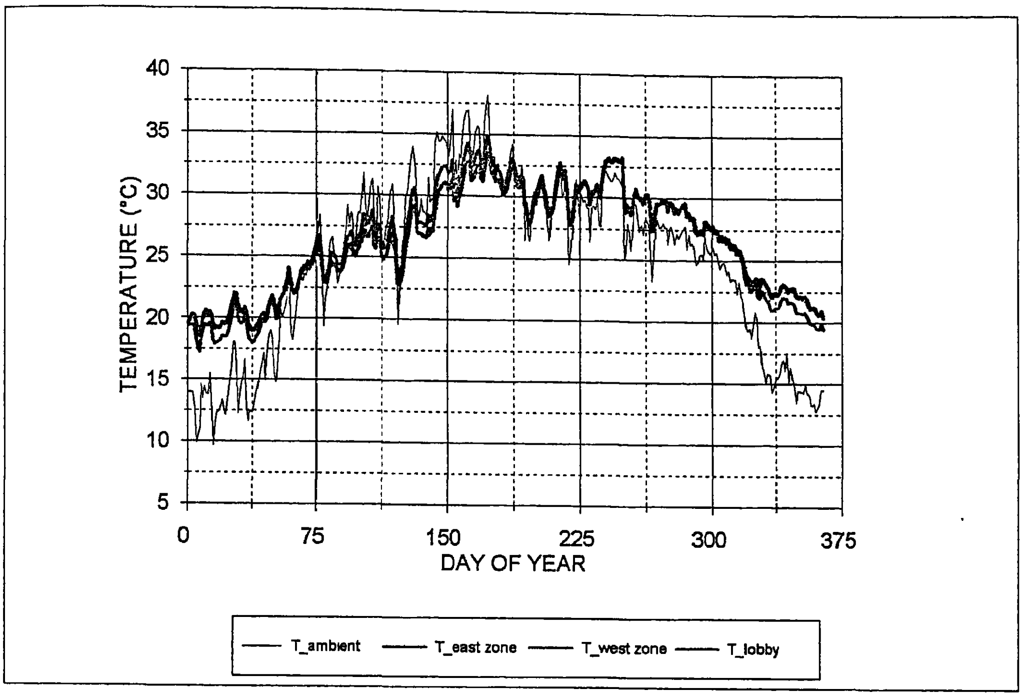

Figure 7: Daily average temperatures in the three zones of the SEC guest house.

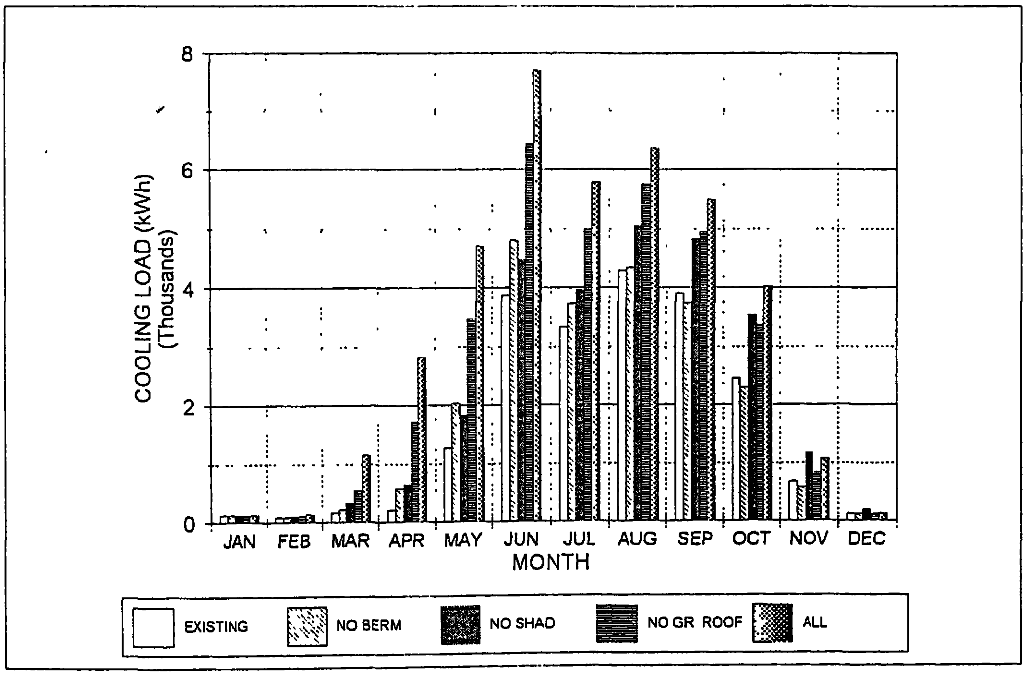

Figure 8: Monthly cooling loads in SEC guest house for five different cases - (i) Existing, (ii) Without earth berming, (iii) Without shading of walls and windows, (iv) Without terrace garden, and (v) a combination of the last 3 cases.

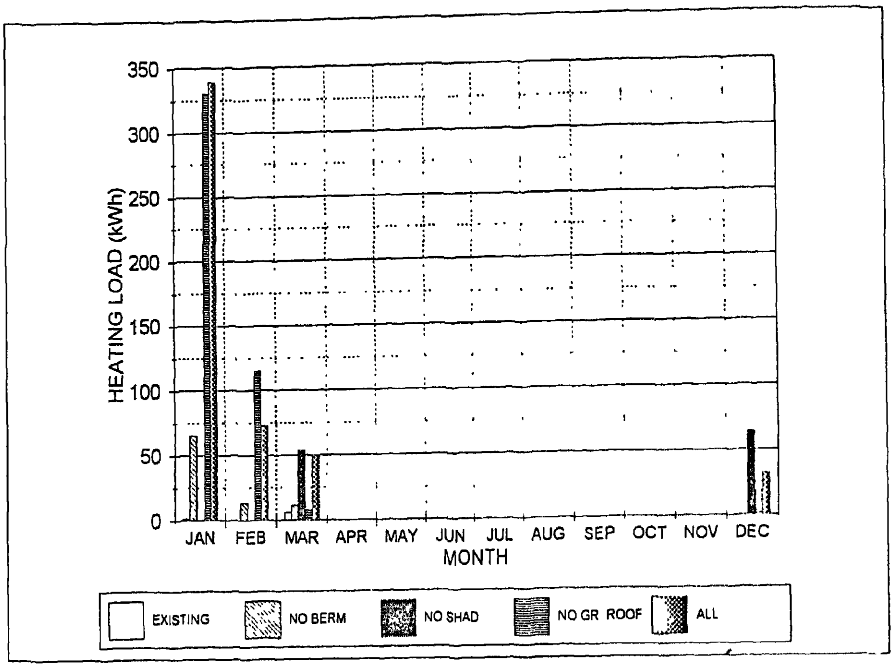

Figure 9: Monthly heating loads in the guest house for the same cases of Figure 8.

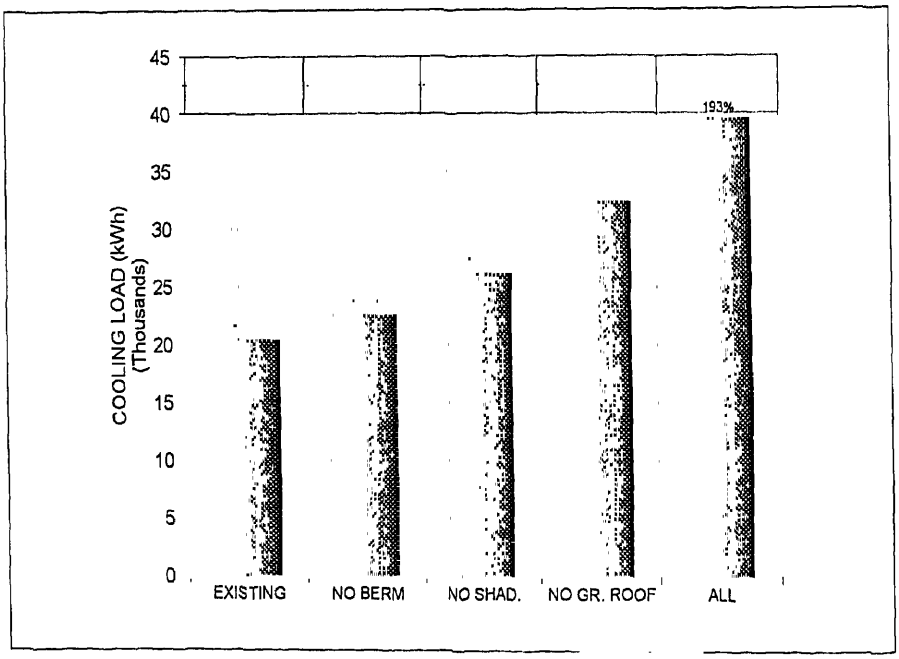

Figure 10: Annual cooling loads in the guest house for 5 different cases.

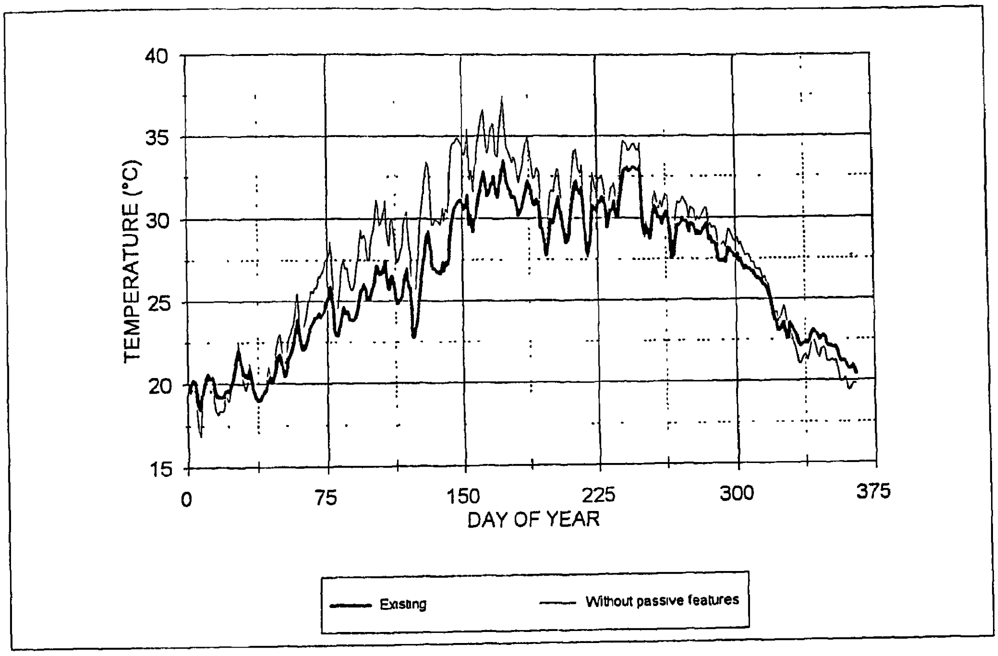

Figure 11: Average daily indoor temperatures in the guest suites for the existing and the theoretically converted guest house (without passive solar features).

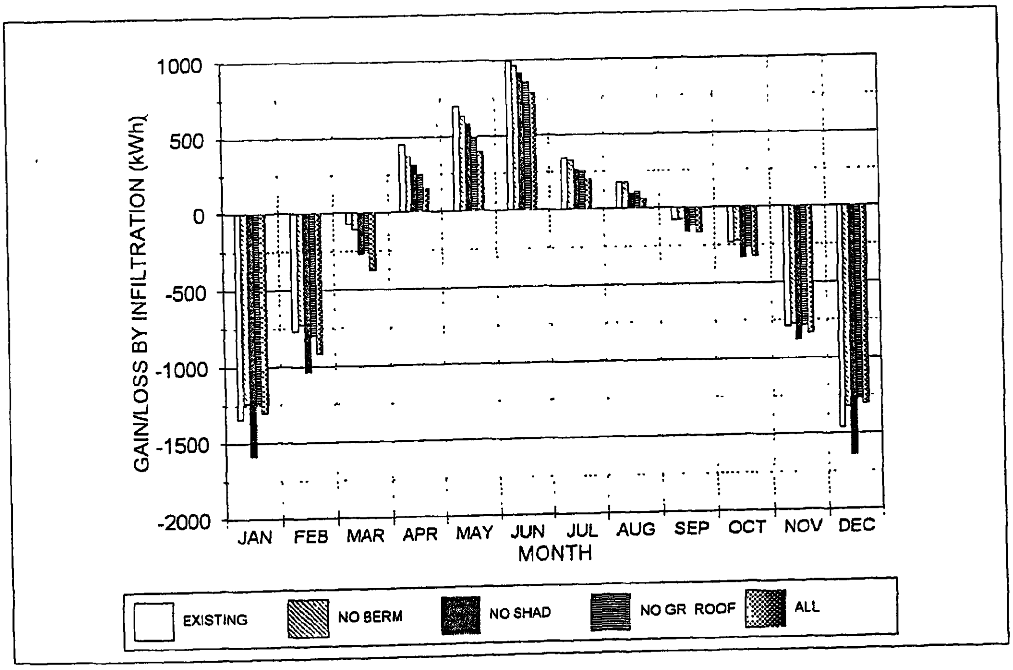

Figure 12: Monthly heat losses from (and gains to) the guest house because of fixed infiltration rate (1.0 air change per hour).

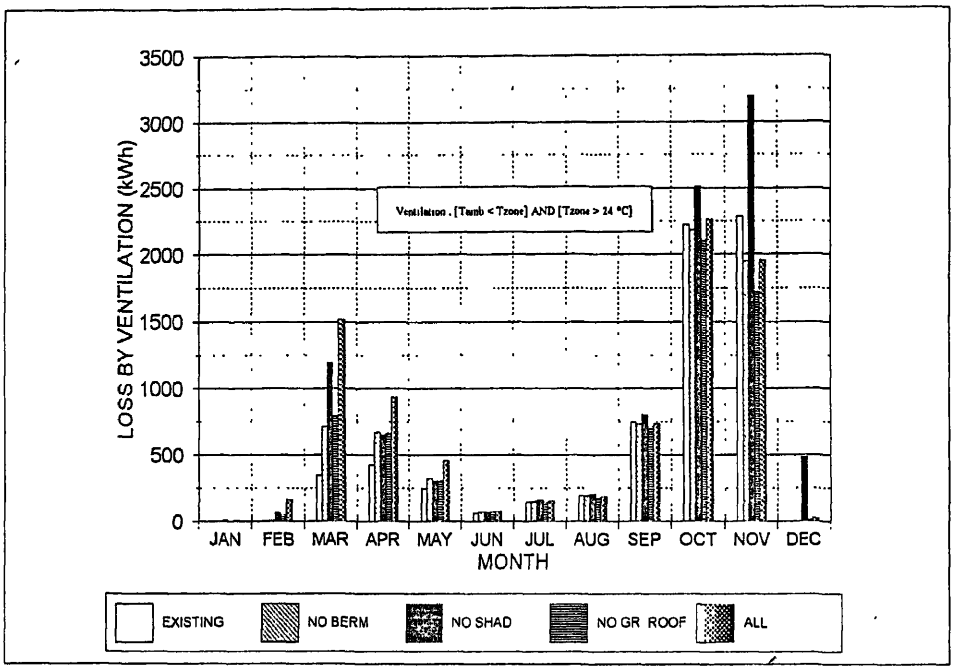

Figure 13: Monthly heat losses due to the simulated ventilation in the guest house.

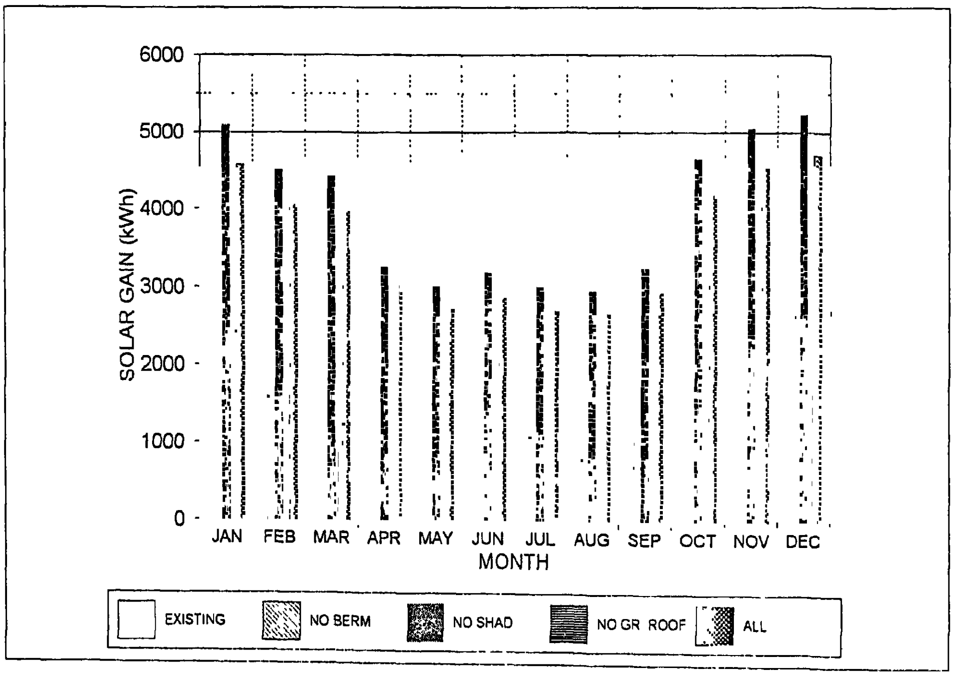

Figure 14: Monthly solar gains in the guest house for the 5 cases of Figure 8.

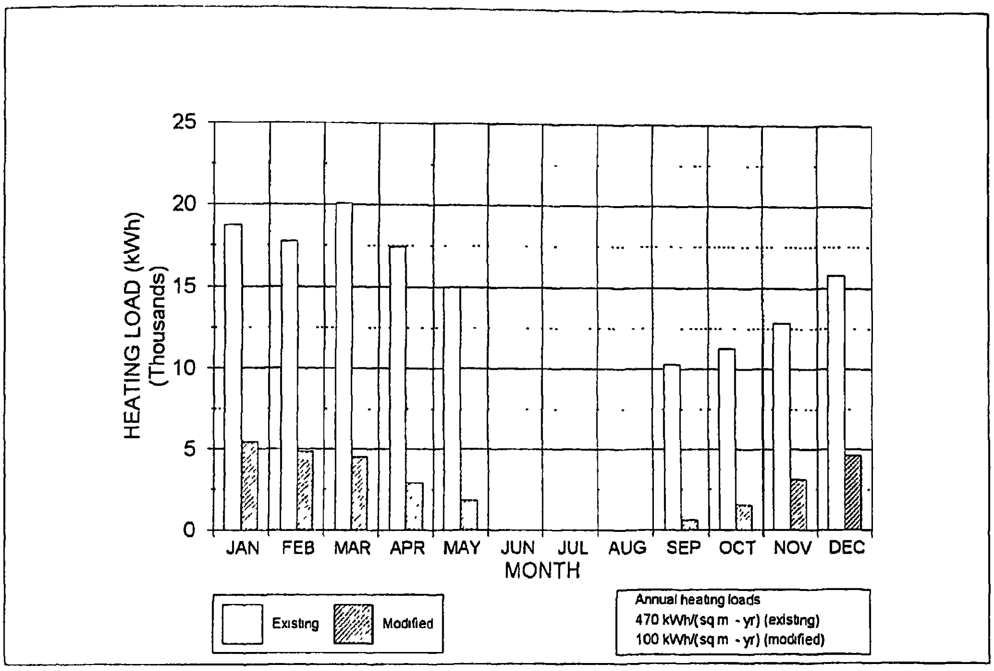

Figure 15: Monthly heating loads in the existing and theoretically modified guest house to suite German climate (Wurzburg).

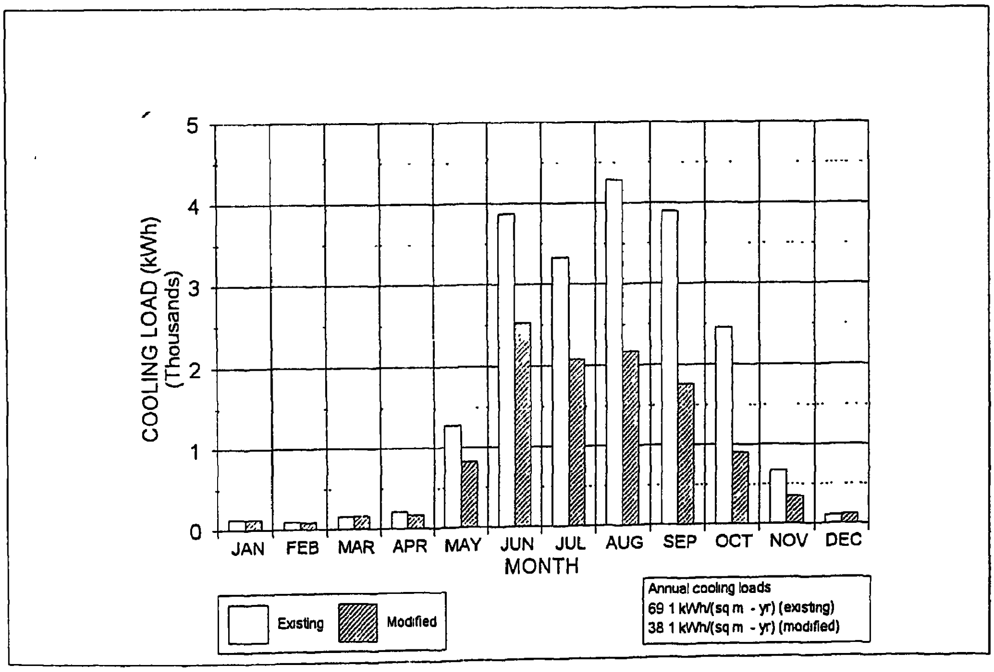

Figure 16: Monthly cooling loads in the existing and modified guest house simulated in the climate of New Delhi, with shadings of walls and windows and favourable ventilation added to the house during simulation.

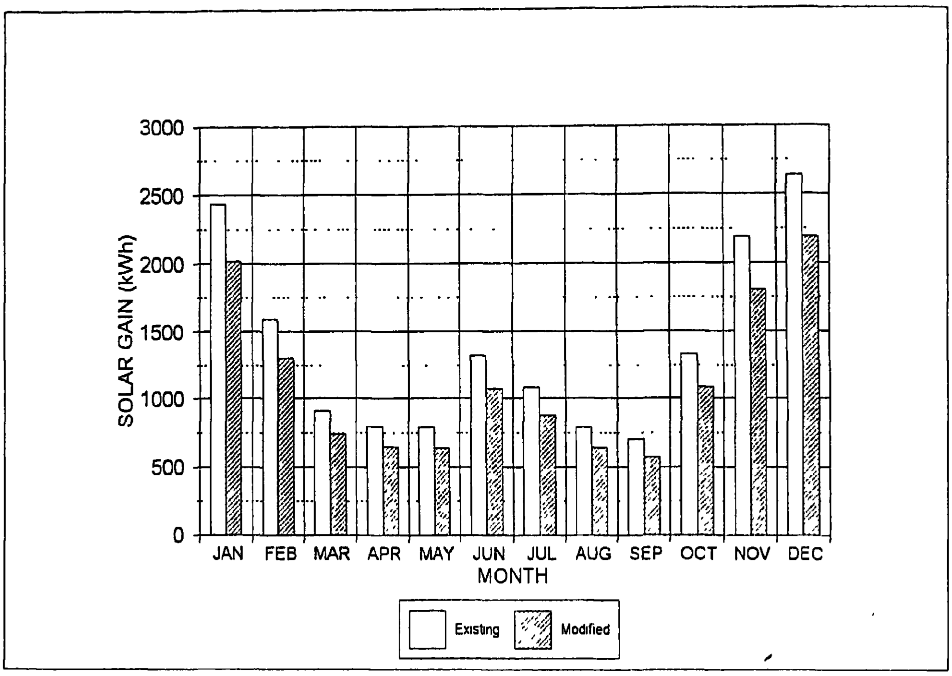

Figure 17: Monthly solar gains in the existing and modified guest house.

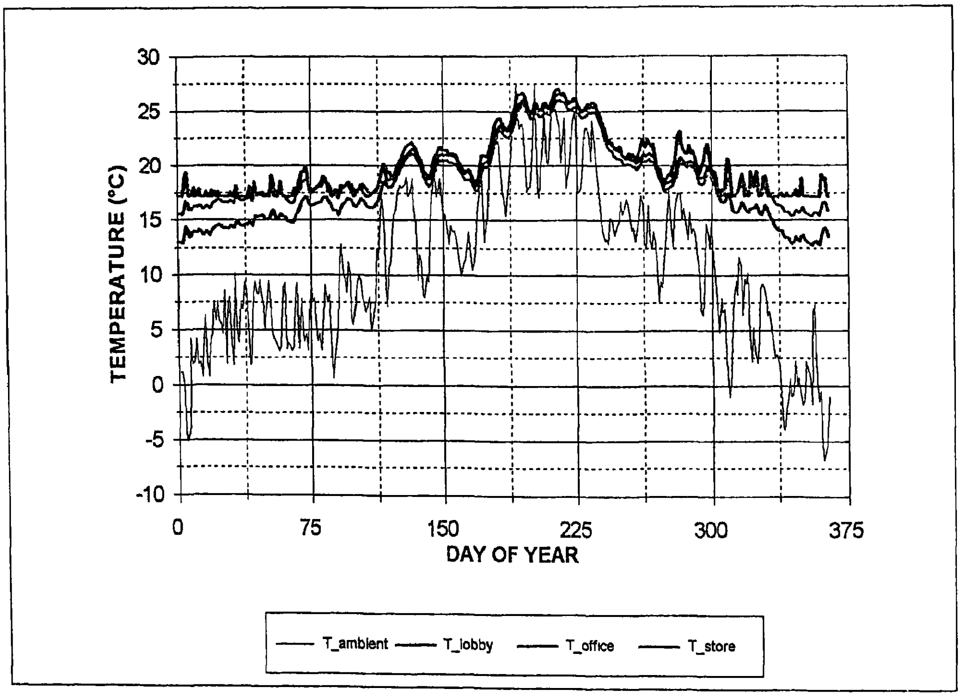

Figure 18: Daily average temperatures in the three zones of the Issum office building plotted with the measured ambient air temperatures.

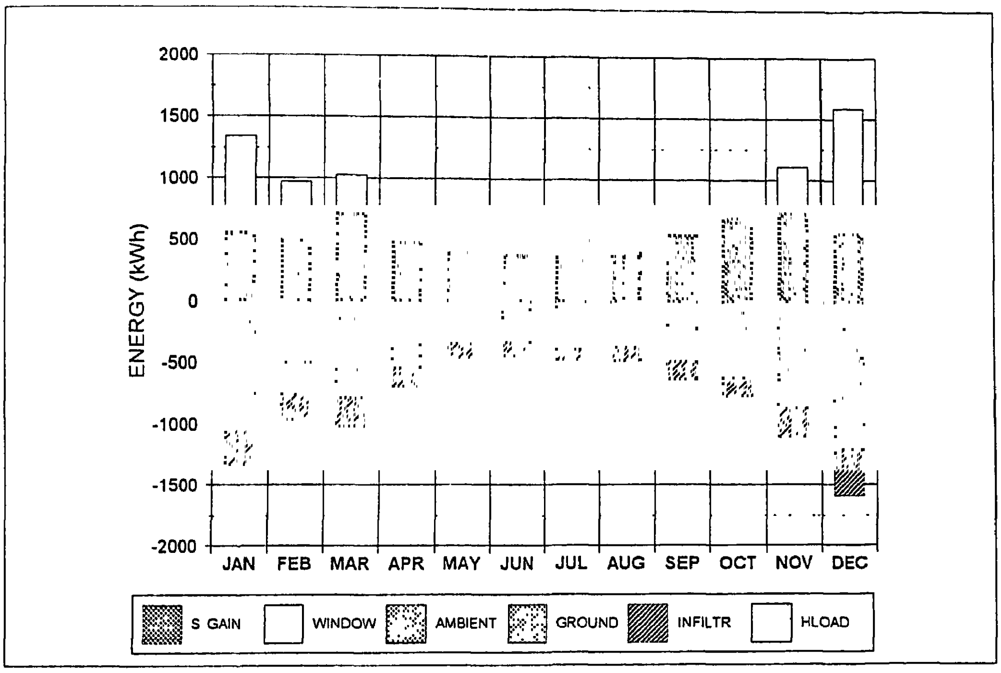

Figure 19: Monthly energy balance for Issum office simulated by SUNCODE.

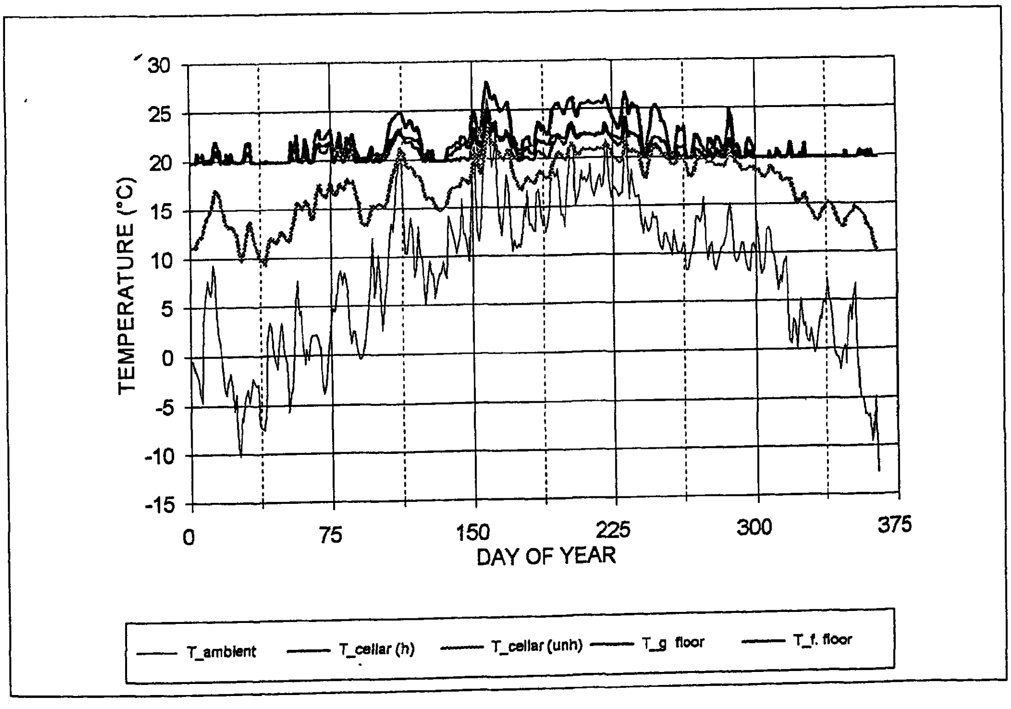

Figure 20: Daily average temperatures in the four zones of the multi-family house in Witten plotted with the measured ambient air temperatures.

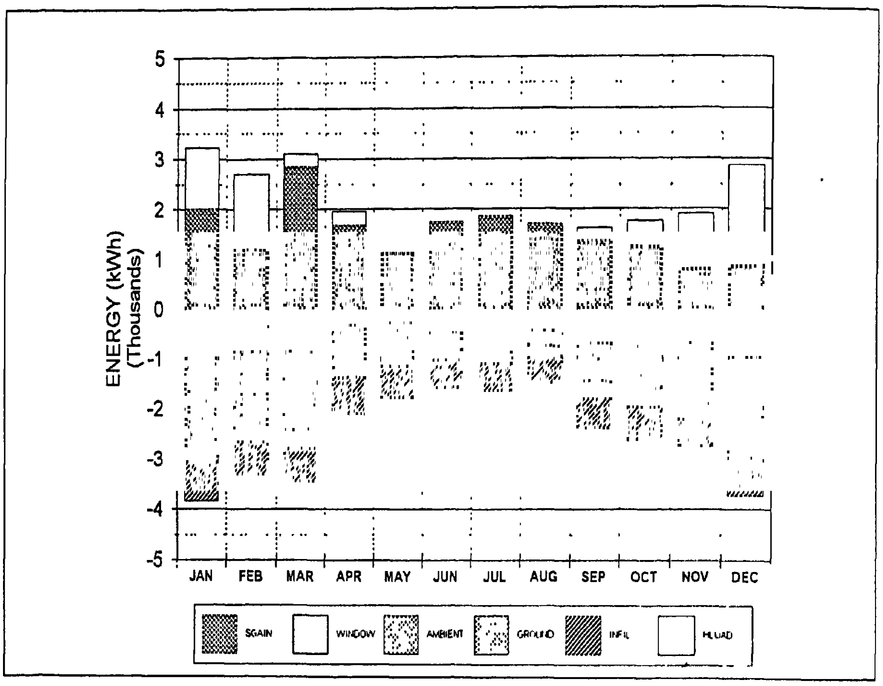

Figure 21: Monthly energy balance for the multi-family house in Witten simulated by SUNCODE.

❺ Comparison of results & their discussion

The results of SUNCODE simulations discussed in the last chapter, and simular results obtained from TRNSYS simulations are compared in this chapter with the measurements in both the German buildings. The degree of agreement between the simulated and measured results is highlighted in all the cases which leads to successful validation of the simulation programs under consideration.

5.1 Measurement and simulation of Issum office

The useful simulated and measured parameters, namely zone air temperatures, heating loads and heat exchange due to ventilation, are compared in Figures 22 - 26, and are discussed below

5.1.1 Zone temperatures

The zone air temperatures in the office and store are plotted in Figures 22 and 23 respectively, where clearly the agreement between the two simulated temperatures (SUNCODE and TRNSYS) is better than that between the simulated and measured ones. The broken line of measured temperatures indicates the missing data.

The measured temperature profile is followed well by the simulated profiles during the summer months, but the measured winter-time variations are not exhibited by the simulation The daily average simulated temperatures in office and store differ at the most by 2 °C at a few places except for the month of December where the differences are larger in the case of the store. The higher temperature in store might be due to some additional internal gain or due to the opening of door between the store and office for longer periods than simulated.

The measured temperature also goes below the set-point temperature which indicates occasional events (e.g. closing of office for a few days) of which no information was available. The set-point temperatures are generally lowered in practice in such cases.

5.1.2 Heating loads and solar gains

The simulated and measured heating loads plotted as bars in Figure 24 differ by a significant amount for certain months. SUNCODE, in general, has predicted smaller loads than TRNSYS and both programs predict smaller than measured loads in the building. The smaller loads predicted by SUNCODE can be attributed to the higher solar gains of Figure 25. The annual predicted load varies from the measured load by 7.4 % (SUNCODE) and by 1.3 % (TRNSYS[9]). Similarly the annual solar gain calculated by TRNSYS is 13.3% smaller that that calculated by SUNCODE. Solar gain calculations by SUNCODE have been explored in an earlier study[10], and confirm that the thermo-optical properties that the program attributes to the glazings are valid only for normal glass but not for heat protecting glass used in the German buildings selected for the present study.

5.1.3 Ventilation

It is worthwhile to compare also the heat loss by ventilation because of the different ways in which the ventilation is handled by the two programs.

SUNCODE needs a user-defined set-point temperature to start the ventilation of the outside air when the zone air temperature exceeds this value. The program automatically optimizes the air change rate to obtain maximum benefit from ventilation, but the air change rate is never known to the user.

On the other hand, TRNSYS asks the user to input a value of air change rate for ventilation. Also the temperature boundary conditions for the ventilation to start have to be defined in the input deck by combining the differential controllers available in TRNSYS. Therefore, an exact translation of the conditions defining the ventilation from SUNCODE to TRNSYS is difficult. However, an effort was made to build an appropriate logic in TRNSYS to match the ventilation in the two programs. The comparison of heat loss by ventilation during the simulation by two programs (Figure 26) shows the success of this effort.

5.2 Measurement and simulation of the multi-family house

A similar discussion follows on the comparison of simulated and measured results for the multi-family house in Witten.

Daily average air temperatures are compared in Figures 27 -29 for cellar (unheated), ground floor and first floor respectively. The degree of agreement is the same as in the case of the Issum office, but with a few remarkable differences.

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[9] Mode 2 (correlations of Bocs et al) of the radiation processor of TRNSYS has been used during simulations. A discussion of these processors is given in Appendix B.

[10] T. Braeska, A. Kock and A. Niewienda 1996. Softwarelabor für Niedrigenergie- und Solararchitektur. Report, FG Bauphysik und Solarenergie, Universität-GH-Siegen, Germany.

The obvious difference in the temperatures in cellar during winter appears to be caused by highly varying internal gains because several electrical household appliances operate in the cellar. A knowledge of the profile of heat released by these appliances, instead of theoretically tuning the internal gains would improve the simulated results to a great extent. Once again, the variations in the measured temperatures during the winter season are missing in the simulated temperature curves.

The monthly heating energy demands are shown in Figure 30 and the solar gains in Figure 31. SUNCODE has predicted much lower heat demand (24% less than the measured value). The higher solar gains calculated by SUNCODE are already discussed in the previous section. Another important difference arises from the fact that the measured energy included the consumption for both the space and the water heating. The consumption of energy for water heating has been roughly estimated, and subtracted from the total measured consumption. This appears to be the reason for large deviation in the simulated heating loads. The prediction of heating energy demand by TRNSYS, however, has come very close to the measured demand.

Finally, a comparison of heat loss from the house due to ventilation has been shown in Figure 32, and follows the same discussion as mentioned in section 5.1.3.

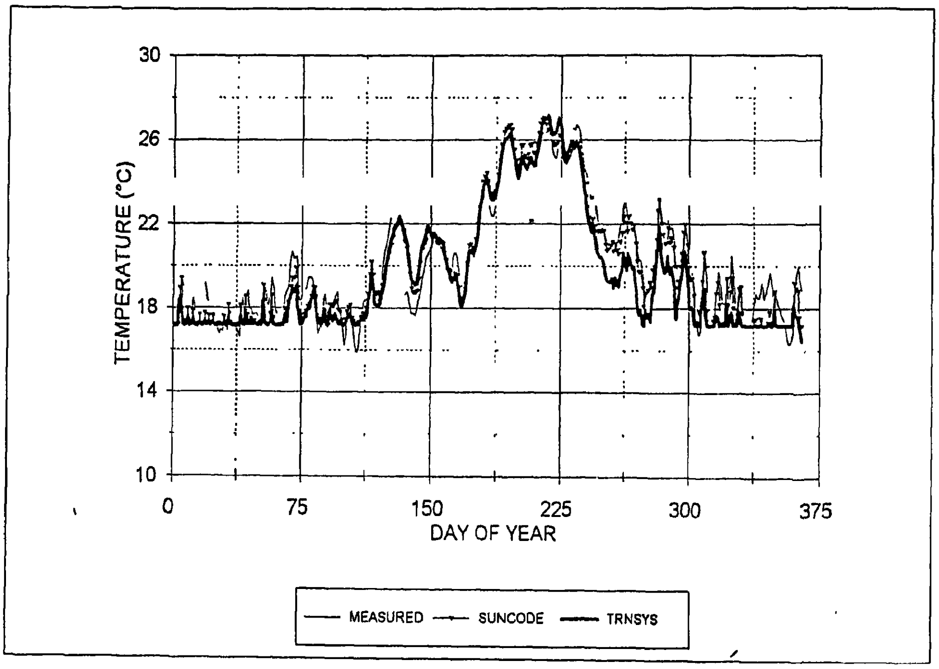


Figure 22: Comparison of the daily average air temperatures in the zone 'office' of the Issum office building. The broken line indicates the missing measurements.

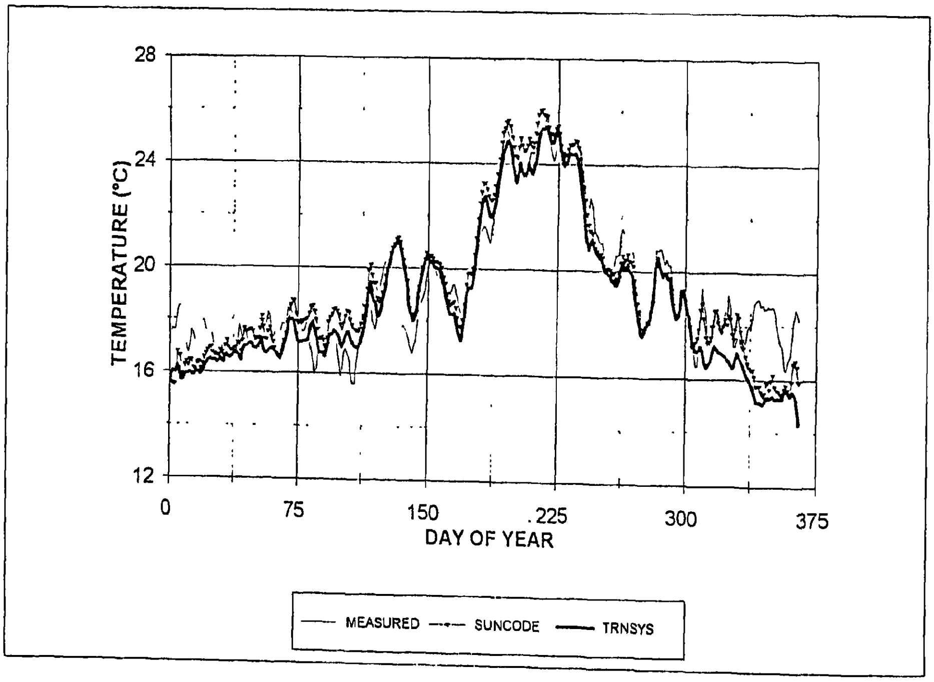


Figure 23: Comparison of the daily average air temperatures in the zone 'store' of the Issum office building. The broken line again indicates the missing measurements.

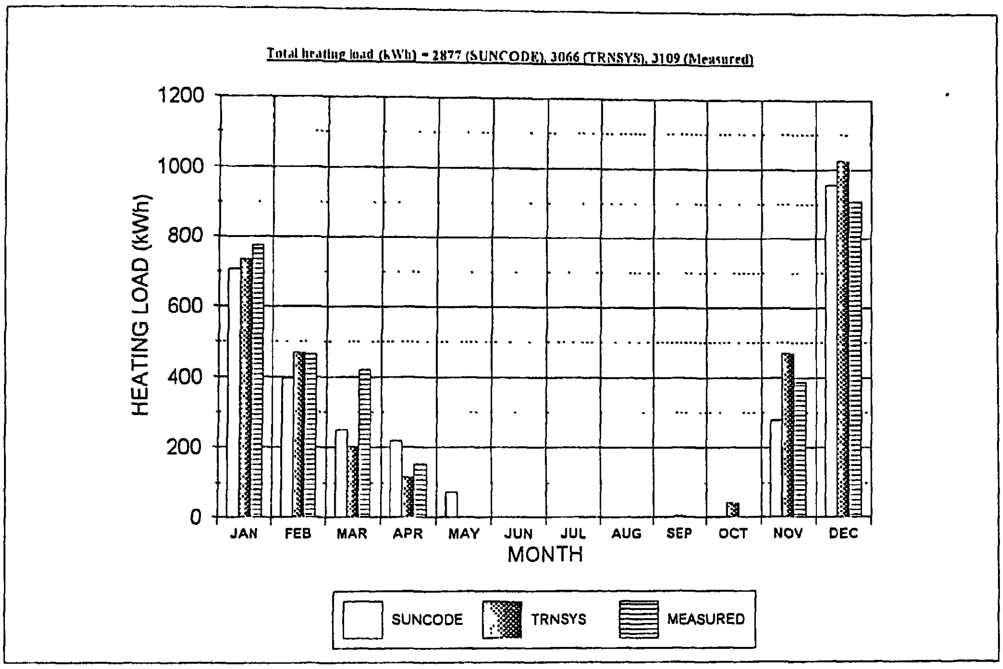


Figure 24: Comparison of the simulated monthly heating loads in Issum office building with measurements

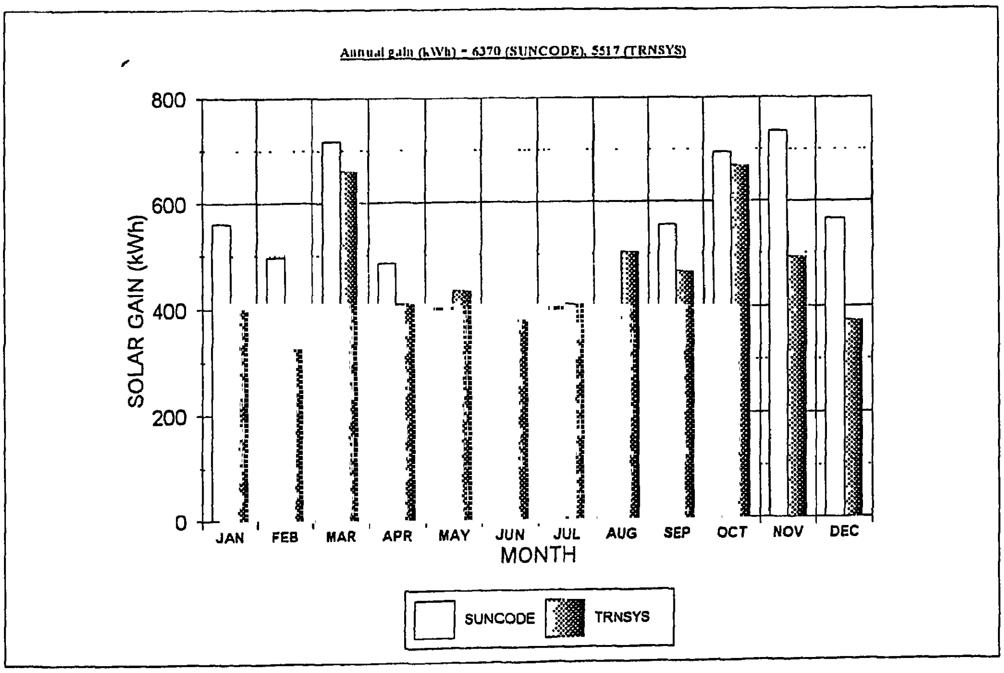


Figure 25: Comparison of the monthly solar gains calculated by SUNCODE and TRNSYS for the Issum office building.

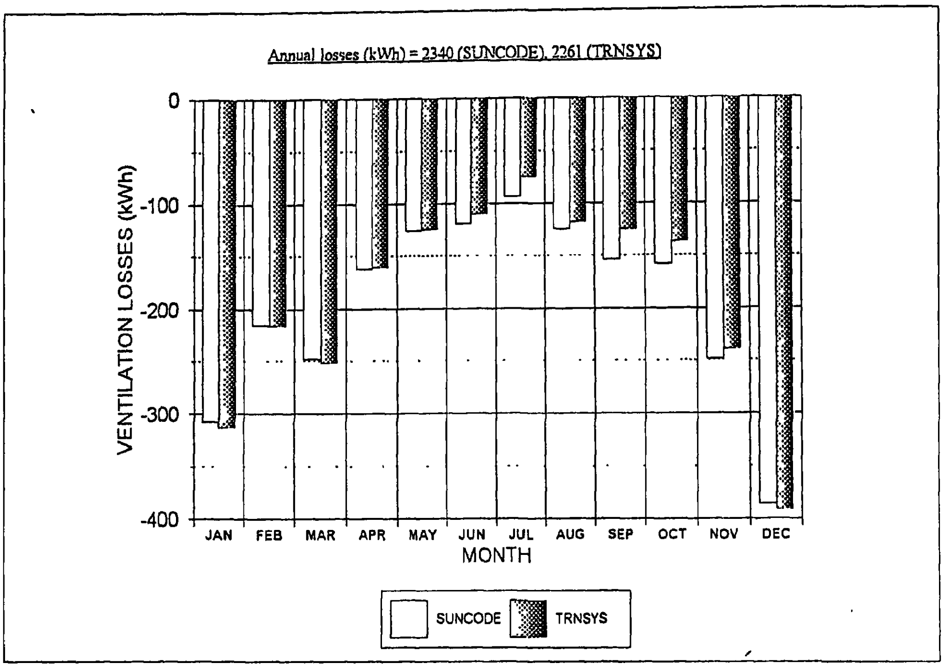


Figure 26: *Comparison of the monthly energy losses due to ventilation simulated by SUNCODE and TRNSYS for the Issum office building.*

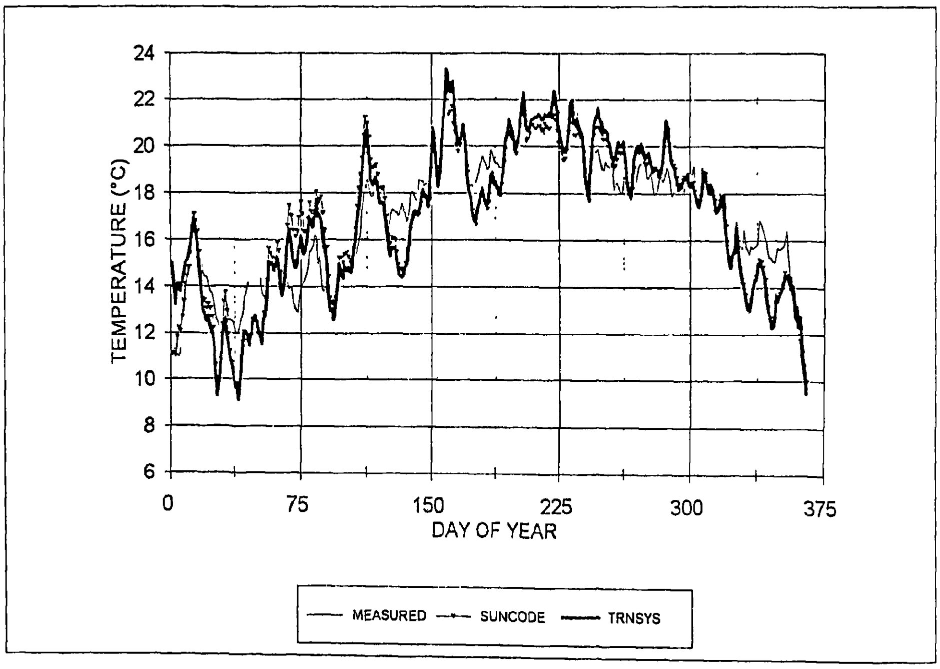


Figure 27: *Comparison of the daily average air temperatures in cellar (unheated) in the multi-family house in Witten. The broken line indicates the missing measurements.*

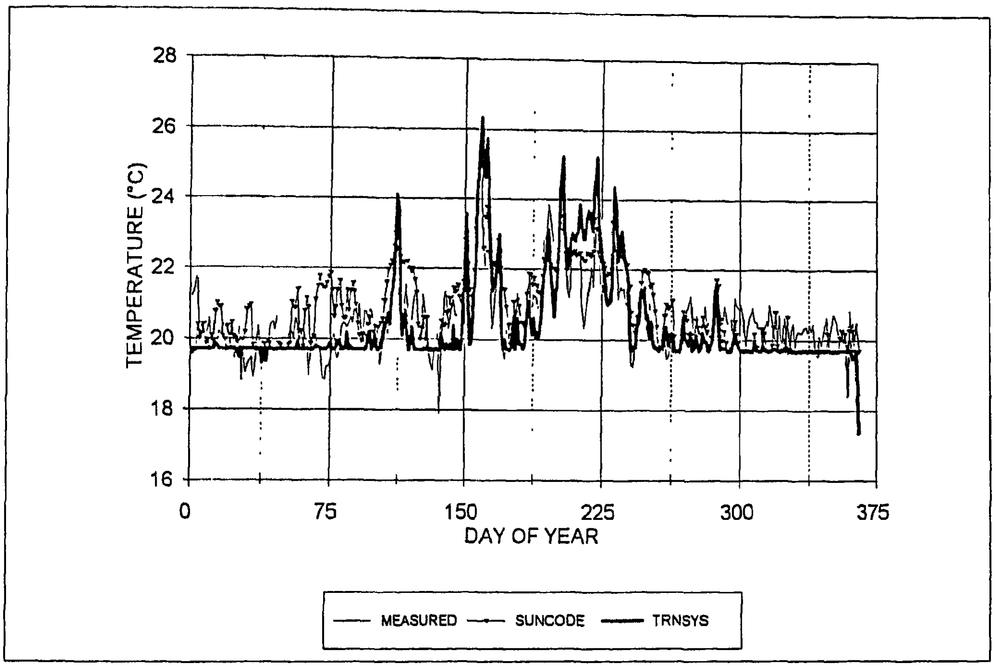


Figure 28: Comparison of the daily average air temperatures in the ground floor of the multi-family house in Witten.

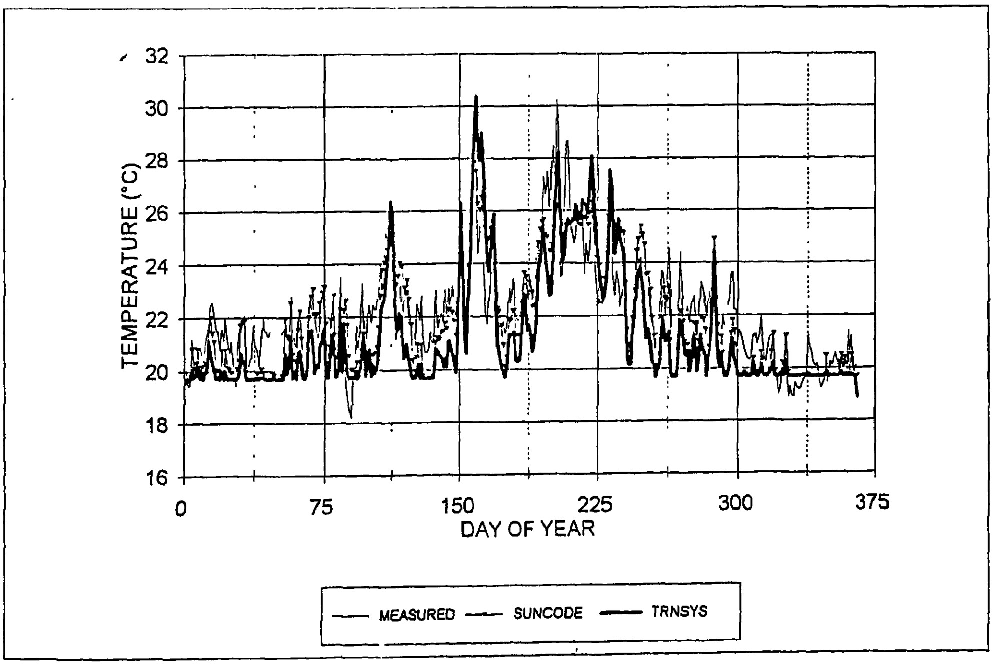


Figure 29: Comparison of the daily average air temperatures in the first floor of the multi-family house in Witten.

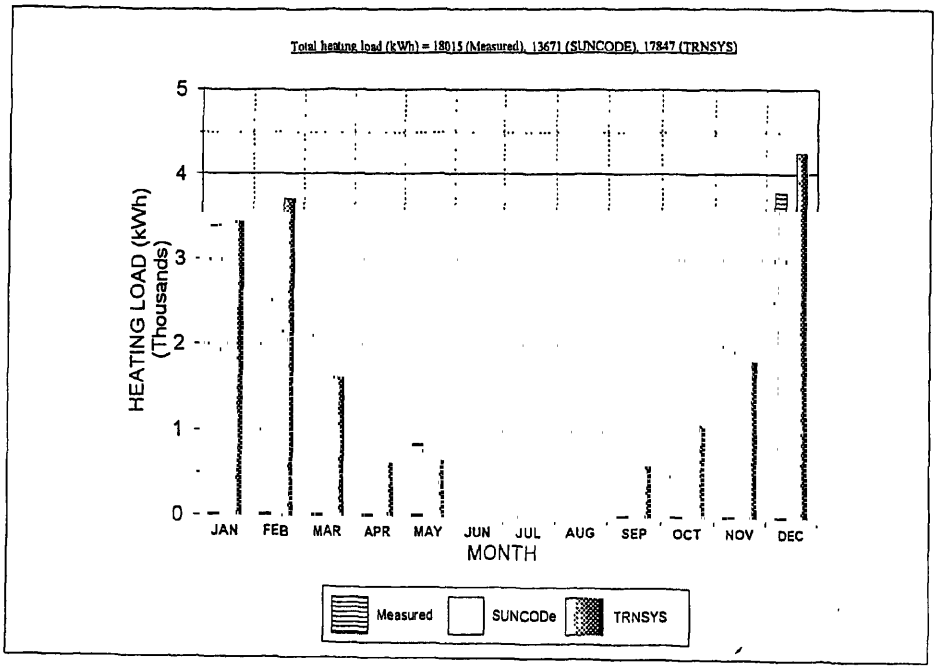


Figure 30: Comparison of the simulated monthly heating loads in the multi-family house in Witten with measurements

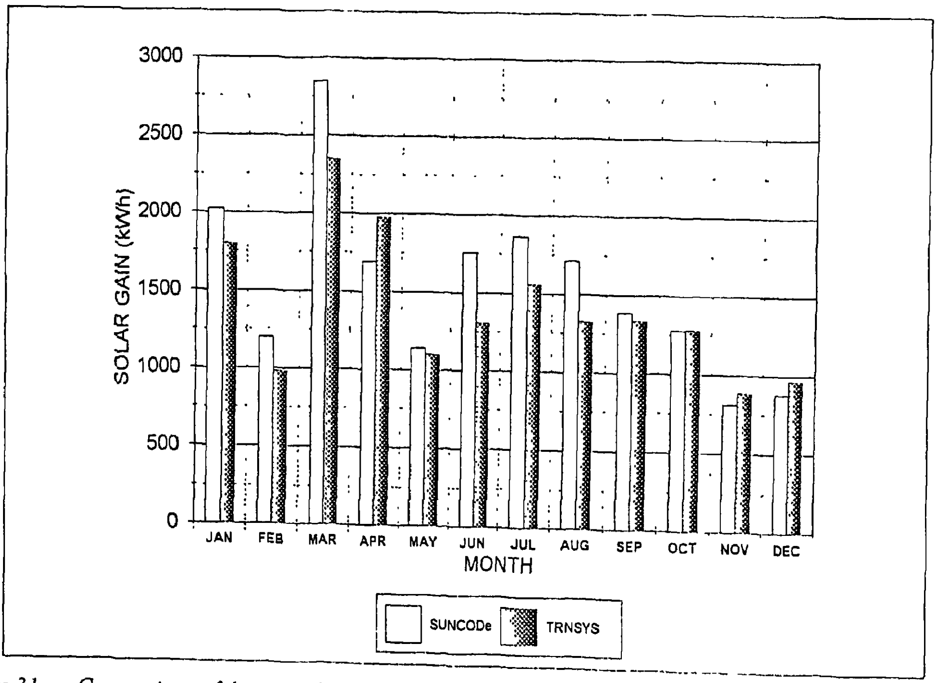


Figure 31: Comparison of the monthly solar gains calculated by SUNCODE and TRNSYS for the multi-family house in Witten.

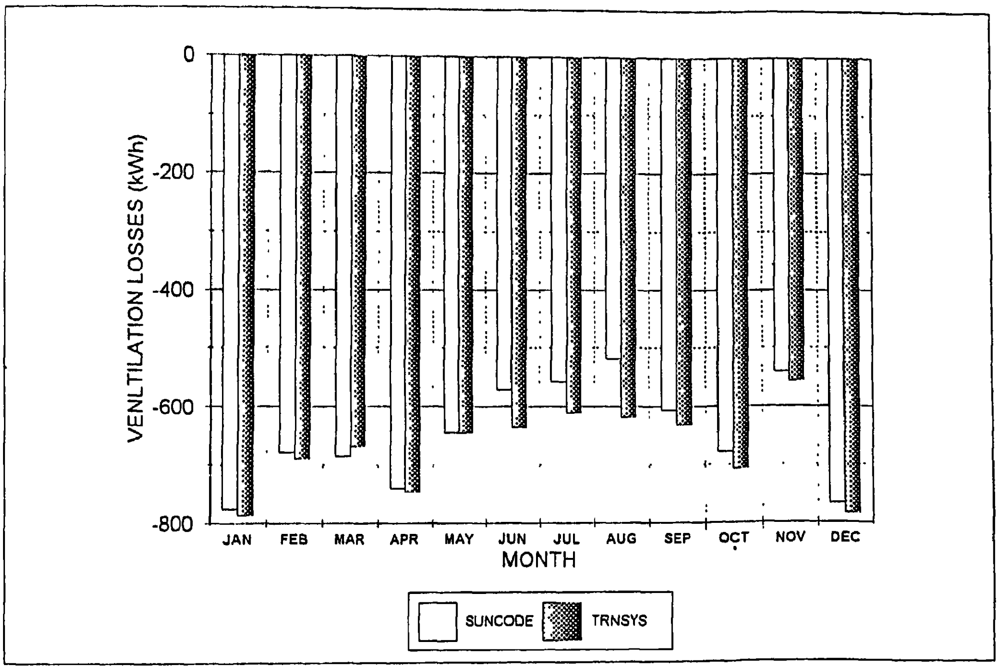


Figure 32: Comparison of the monthly energy losses due to ventilation simulated by SUNCODE and TRNSYS for the multi-family house in Witten.

❻ Conclusions

6.1 Conclusions

The conclusions drawn from the discussions on the results of various exercises in the preceding chapters are summarized below.

1. It is essential to use the program SOMBRERO for the calculations of hourly shading coefficients on the building exteriors by a variety of obstructions. It is easy to couple this user-friendly program with TRNSYS and SUNCODE because of the built-in processors for the desired output. The coupling greatly improves the accuracy of the simulated results.

2. A building's form and orientation have a significant influence on its thermal performance because of changing shading patterns on walls and windows in a hot climate/season which can be used for improving the performance of the building.

3. The simulation of SEC guest house has shown that passive solar features can tremendously improve the energy efficiency of a building even in a difficult climate like that of Delhi (the efficiency of the guest house was observed to have increased by about 50% because of its passive solar features). At the same time, these features increase the level of indoor thermal comfort. The passive features studied in this house were earth berming (earth shelter), shading of windows and walls and terrace garden.

4. A good agreement has been observed between the results of simulations by SUNCODE and TRNSYS, and between the simulated and measured results. Both the programs are therefore well suited for thermal analysis of buildings, and can predict the performance within acceptable limits of accuracy. SUNCODE can easily simulate passive solar features like rockbin storage, Trombe wall etc, but the description of HVAC and other building systems is more accurate in TRNSYS.

5. TRNSYS offers the user a choice from the several models for the processing of solar radiation data. An appropriate model can be selected depending on the type of the given

radiation data. A comparison of the available processors in TRNSYS is shown in Appendix B. The four different models used in the solar radiation processor of TRNSYS show a seasonal inconsistency in their results, and differences up to 30% have been observed in the outputted beam and diffuse radiations for the location of Witten, Germany.

6. SUNCODE, however because of certain limitations of the program, is more suitable for small residential buildings with only a few complexities. The versatility and the flexibility of TRNSYS makes it the preferred program, but the time and manpower required to attain a proficiency in its use come into question.

6.2 Potential sources of error in simulation

Listed below are the possible sources of error that generally affect the results of a simulation exercise, and which may be avoided in future simulations.

1. Little information is available on the user behaviour. A record of the important and isolated events e.g. holidays and vacations when the occupants are not using the building, and user habits of operating the doors and windows would greatly help in improving the results of simulation. A knowledge of these events and the user behaviour can be translated, with a varying degree of accuracy, as inputs for simulation.

2. The operations of heating and cooling systems are generally controlled according to a pre-defined strategy (e.g. it can be dependent on outside air temperature), which should be available to the person running the simulations.

3. The parameters that are measured in a building should match the parameters that result from simulation. Different temperature measurements (whether air temperature, radiant temperature or surface temperature) could lead to rather different conclusions because there are always inherent differences of up to 3 K in these temperatures. Also the location of the sensors needs a careful planning while monitoring a building.

4. The limitations built into a program are sometimes obstacles to accurately model the users' operations in a building. In such cases, although tedious because of the extra burden placed on the user of the program, the simulation period is generally split into smaller parts to obtain the required accuracy in the results.

6.3 Scope for further improvement

The results of simulation can be further improved by using the full capabilities of TRNSYS for better parameter scheduling and for simulating the actual heating plant operation. In the case of SUNCODE, reducing the simulation period and performing a sequence of simulations would overcome the problem of limitations on schedules.

The evaporation of water from terrace gardens which improves the indoor thermal performance significantly in practice in both the buildings (SEC guest house and Issum office) has not been simulated. The influence of terrace garden should be incorporated in the simulations, and needs to be quantified by simulation studies.

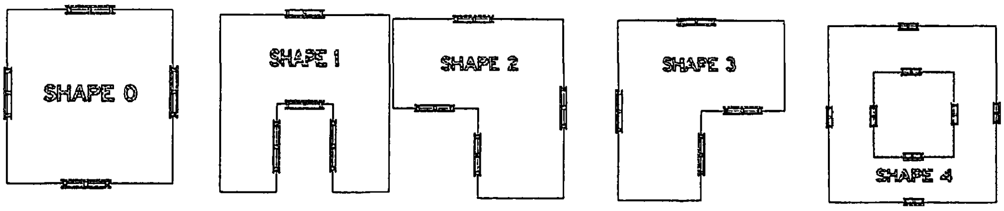
A better planning is suggested to coordinate the simulations and measurements in order to match the zoning of a building, location of sensors, and the performance parameters of interest[11].

---

[11] N.K. Bansal, R. Muthukumar, S.P. Singh and A. Misra 1990. Instrumentation in solar passive buildings. Project report, CES, Indian Institute of Technology, New Delhi, India.

APPENDIX A

The technique of coupling TRNSYS with SOMBRERO has been used to study the effects of external shading on various building shapes. The following five differently shaped buildings having the same floor area (=30 m^2) were considered for this exercise.



Shape 0:	The compact form of the building with a square base (floor).
Shape1:	The building has a U- shape opening towards south direction.
Shape2:	The L- shape of the building form which opens towards west direction.
Shape3:	The same form as in the previous case, but opening towards east.
Shape4:	The building again has a quare base but with a square shaped courtyard in the centre.

The ratio of wall to floor area for these building shapes are:

Shape	Total wall area (m^2)	Wall area/Floor area
Shape 0	66 0	2.2
Shape 1	96.0	3.2
Shape 2	72.0	2.4
Shape 3	72.0	2.4
Shape 4	110.9	3.7

Each side of a building has a total window area of 2.0 m^2. Overhangs and side walls, each being offset along the window edges, have a perpendicular projection of 0.65 m from the respective surfaces.

SOMBRERO has been used to calculate the hourly GSC^s and view factors (for the entire year) for each surface and window which gets shaded during any day of year by overhangs and sidewalls.

The main parameters which were studied after the simulation of each building shape, were the monthly cooling loads shown in figure A1 where the climatic data of Delhi has been used. The cooling loads are, as expected, maximum for the shape 4, because of the largest exposed wall area, even after considering the night cooling by ventilation enhanced by the courtyard. For the same reason, the shape 1 has the second highest cooling load , and the shape 0 the least.

However, the solar gains shown in figure A2, are highest for the basic shape 0 because none of the windows has additional shading by another wall in this case. The solar gains are least for shape 1 where three (out of four) windows are shaded by adjacent walls for major part of a day.

The ventilation of the building in each case has been controlled according to the following condition (considered in all previous cases too):

Ventilation is switched on when:	*Zone Temperature > Ambient temperature* *AND* *Zone Temperature > 24°C*
Ventilation rate: *(Air changes per hour)*	*[Zone temp. - Amb. Temp.]/2 or a max. of 5.0*

Thus the ventilation helps in reducing the coolng loads, specially during spring and autumn which are plotted in figure A3.

It may be concluded, therefore, that the compact shape of the building (shape 0) is best suited for hot climates, provided the ventilation is controlled favourably to realize the minimum energy consumption on cooling. The shading of windows is important, but there should be a provision for availability of good daylight inside the building.

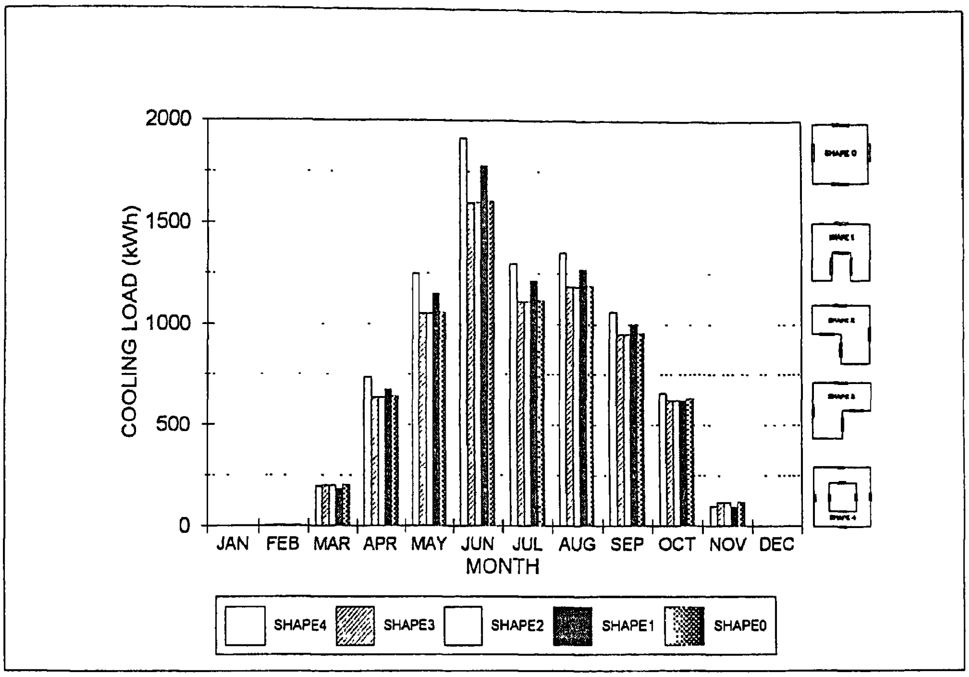


Figure A1: Cooling loads calculated by TRNSYS and coupled to SOMBRERO for the various building forms having the same floor area (=30m²).

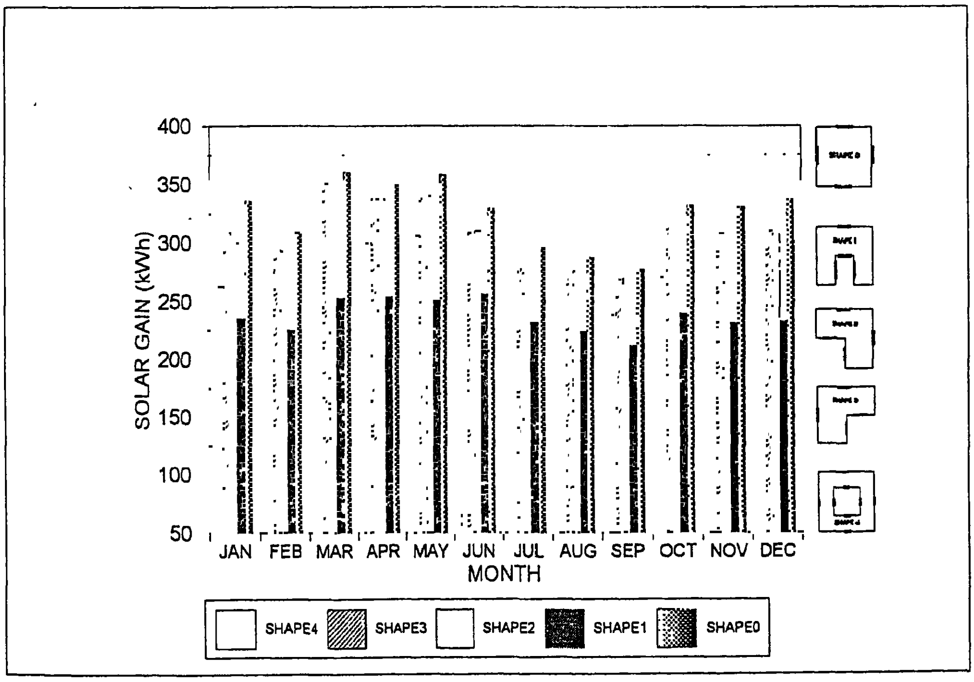


Figure A2: Monthly solar gains for five different building forms.

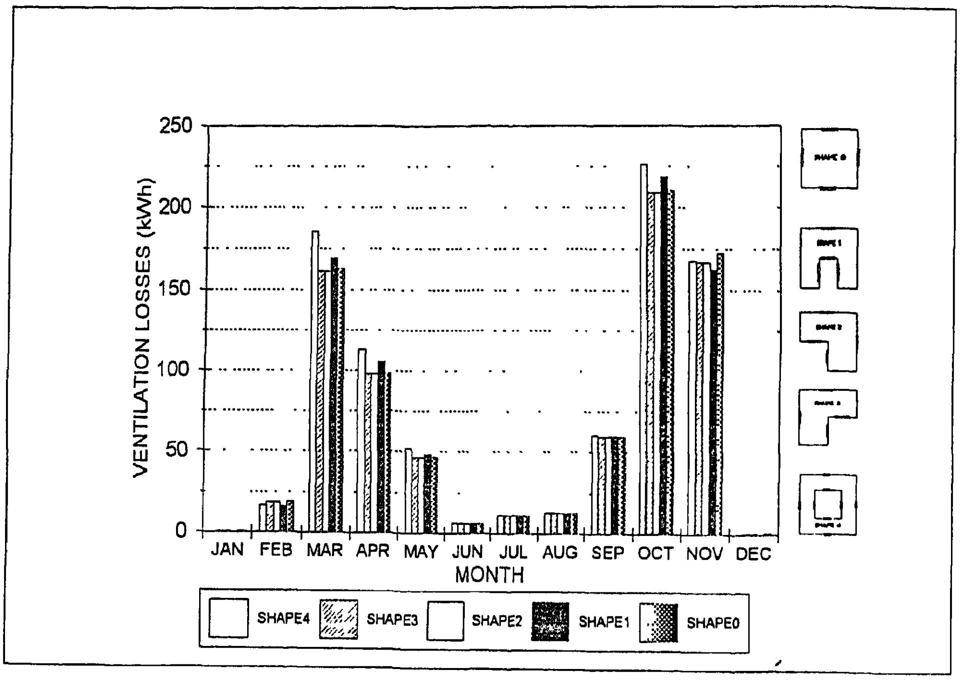


Figure A3: Comparison of heat losses from different building forms due to ventilation.

APPENDIX B

Comparison of radiation models

TRNSYS has a separate solar radiation processor to calculate beam and diffuse radiation on a horizontal surface from total radiation data for horizontal surface. The user can choose one of the four models which are available for the processing of the solar radiation data. The basic correlations used in these models are as follows:

[$k_T = I/I_0$. *Beam radiation is determined by the equation* $I_b = I - I_d$]

[k_T=*Clearness index*; S_c=*Solar constant*: α=*Solar altitude∠*; I_{dn}= *Direct normal beam radiation*]

Model 1: Boes et al

$$
\begin{aligned}
I_{dn} &= (1.3304 \cdot k_T - 0.3843) \cdot S_c \\
I_{dn} &= \max(0,\ \min(I_{dn},\ 0.739\ S_c)) \\
I_b &= I_{dn} \cdot \cos(\theta_z) \\
I_d &= I - I_b
\end{aligned}
$$

Model 2: Erbs

$$
\begin{aligned}
I_d/I &= 1.0 - 0.9 \cdot k_T \qquad \ldots for\ k_T \le 0.22 \\
I_d/I &= 0.9511 - 0.160 \cdot k_T + 4.388 \cdot k_T^2 - 16.638 \cdot k_T^3 + 12.336 \cdot k_T^4 \\
&\qquad \ldots for\ 0.22 < k_T < 0.80 \\
I_d/I &= 0.165 \qquad for\ k_T \ge 0.80
\end{aligned}
$$

Model 1: Reindl reduced correlation

Interval: $0 \le k_T \le 0.3$; *Constraint*: $I_d/I \le 1.0$

$$I_d/I = 1.020 - 0.254 \cdot k_T + 0.0123 \cdot \sin(\alpha)$$

Interval: $0.3 \le k_T \le 0.78$; *Constraint*: $0.1 \le I_d/I \le 0.97$

$$I_d/I = 1.400 - 1.749 \cdot k_T + 0.177 \cdot \sin(\alpha)$$

Interval: $0.78 \le k_T$; *Constraint*: $0.1 \le I_d/I$

$$I_d/I = 0.486 \cdot k_T - 0.182 \cdot \sin(\alpha)$$

Model 1: Liu and Jordan

$$I_d / I = 1.0045 + 0.04349 \cdot k_T - 3.5227 \cdot k_T^2 + 2.6313 \cdot k_T^3$$

The measured total solar radiation on horizontal was decomposed into beam and diffuse radiation using all the four correlations. The sample output is shown in figures B1 - B4 where hourly beam and diffuse radiations are plotted for five successive days in January and June. There are only small differences observed in the four results. Liu & Jordan correlations give relatively higher values of beam radiation for January, while the values calculated by Boes model are higher for June. Erbs and Reindl correlations give lowest values in both the months. Consequently the diffuse radiation is higher as calculated by Erbs and Reindl models.

The maximum difference between the highest and lowest values (from the four models) is about 20% for the peak in beam radiation, and is about 30% for the peaks in the curves of diffuse radiation.

The values provided by the Boes model have been used for generating the radiation data for the building simulations.

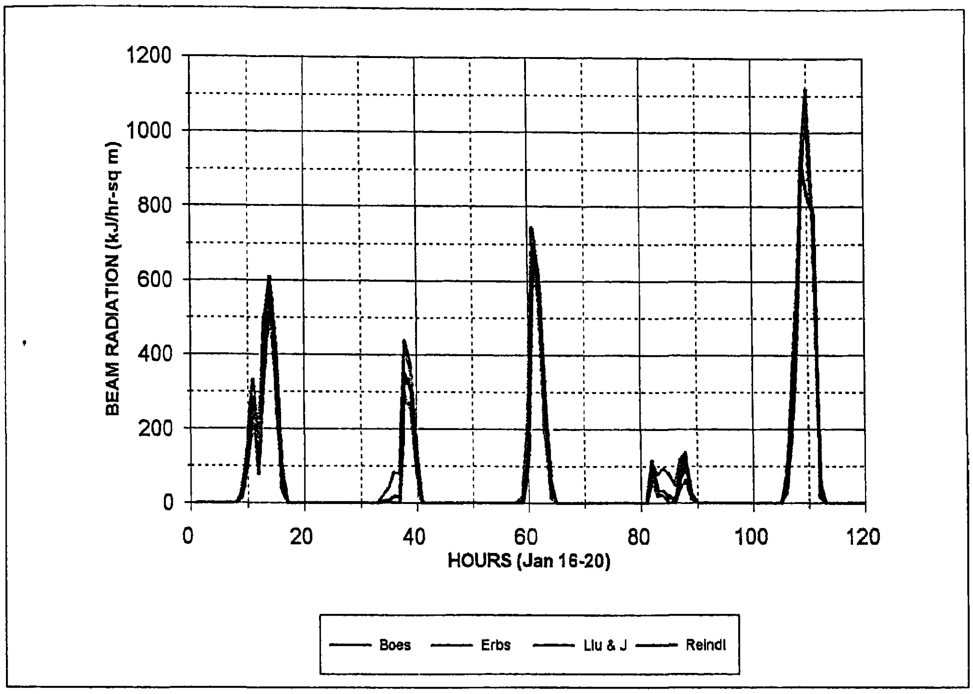


Figure B1: Comparison of four radiation models of TRNSYS - beam radiation on horizontal calculated from total radiation on horizontal in Witten (Germany) for 5 days in January (16 - 20).

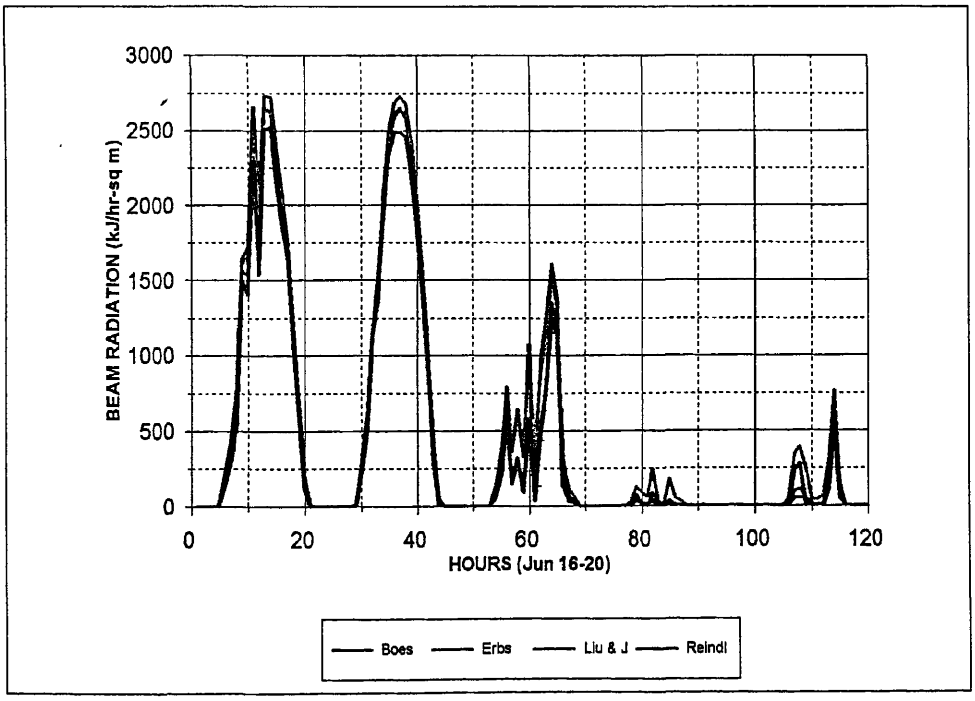


Figure B2: Comparison of four radiation models of TRNSYS - beam radiation on horizontal calculated from total radiation on horizontal in Witten (Germany) for 5 days in June (16 - 20).

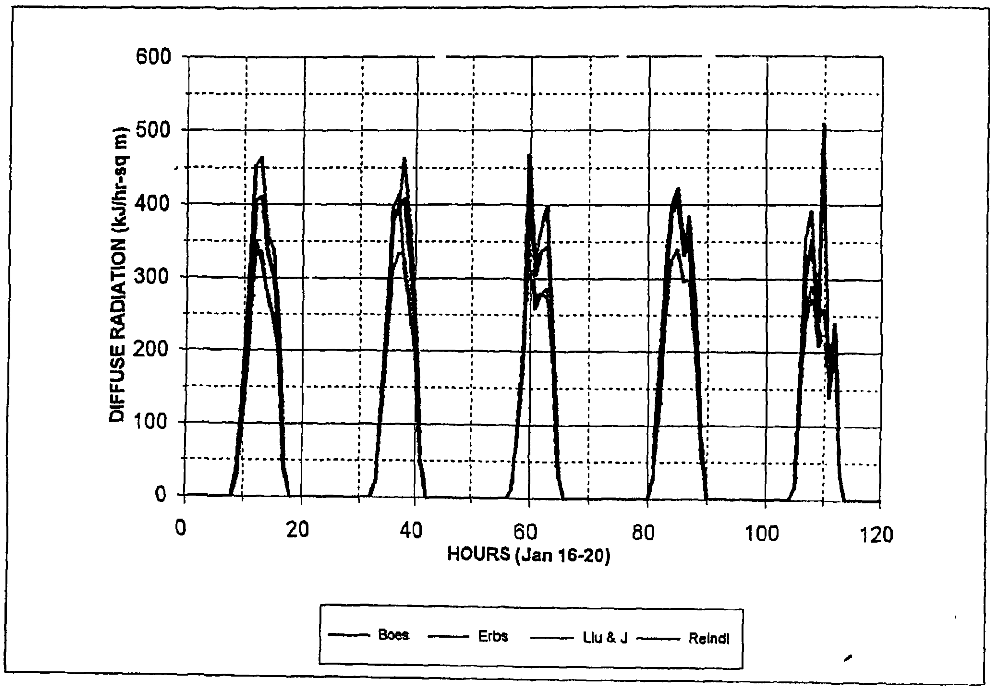


Figure B3: Comparison of four radiation models of TRNSYS - diffuse radiation on horizontal calculated from total radiation on horizontal in Witten (Germany) for 5 days in January (16 - 20).

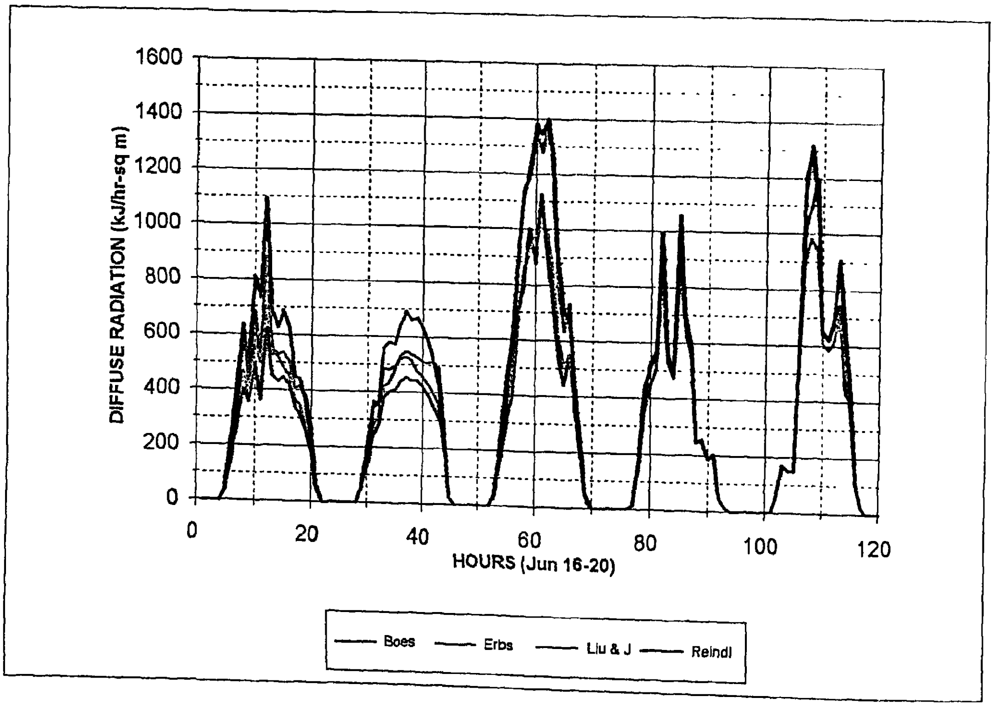


Figure B4: Comparison of four radiation models of TRNSYS - diffuse radiation on horizontal calculated from total radiation on horizontal in Witten (Germany) for 5 days in June (16 - 20).